the radiation, measured with a long-wave IR spectrometer [4] and recalculated to allow for the echelette distribution function, or compared with the radiation from a PRK-4 lamp in the far IR [8]. We see that the radiation data lie close to the resonance-absorption curve determined for the same conditions. The radiation maximum is approximately in the region of the plasma frequency of the drops. The measured dependences of the radiation intensity on the temperature and on the excitation level exhibited a threshold behavior, just as in the transmission measurements. All these facts allow us to state that the observed radiation is dipole radiation of electron-hole drops, resulting from thermal excitation of plasma oscillations in the drops.

On the basis of the obtained data, with allowance for the measured absorption coefficient of the electron-hole drops in the region of their plasma frequency, we can estimate the drop temperature by considering the drop as a quasi-equilibrium system and using Kirchhoff's law. The effective drop temperature determined in this manner is quite high, 12 - 15°K. This agrees quite well with the theoretical boiling temperature of the drops, $T_{theor} \sim 10°K$, which can be estimated from the energy difference of the electron-hole pairs in an exciton gas and in the condensed phase ($\Delta E \approx 4.6$ meV according to the data of [3]). It is quite probable that under the experimental conditions the electron-hole drops are in the boiling state.

We note that the described phenomena were observed, with some differences, in other germanium samples, including some doped up to a density $\sim 7 \times 10^{15}$ cm^{-3}.

The authors are grateful to B. M. Vul for interest in the work and to L. V. Keldysh for a detailed discussion of its results and for certain estimates.

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MOTION OF ELECTRON-HOLE DROPS IN GERMANIUM

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Submitted 12 August 1969
ZhETF Pis. Red. 10, No. 7, 309 - 313 (5 October 1969)

The possible formation of a condensed phase of electron and holes in semiconductors at higher exciton density and at low temperatures was pointed out in [1]. Experimental observation of the condensate in germanium and in investigations of absorption and radiative recombination was reported in [2] and [3].

One of the most characteristic features of such a condensed state, namely of electron-hole (EH) drops, should be their extremely high mobility. Indeed, scattering by phonons of the electrons and holes contained in the drops is suppressed compared with the scattering of the free carriers at the same temperature, owing to the Fermi degeneracy present in the drop, and decreases with decreasing temperature like T^5 [4]. Estimates for germanium, assuming that the equilibrium concentration in the drop is $n_0 \sim 10^{17}$ cm^{-3} [3, 4] give for the free-path time relative to phonon collisions a value $\tau \sim 10^{-6} - 10^{-7}$ sec at 2 - 4°K. Besides the emission and absorption of phonons by individual carriers, the drop, as a system bound by internal forces, can emit and absorb as a unit, and thus experience a change in its translational velocity. Such processes, however, become possible only when the drop velocity exceeds that of sound. It seems likely that the drops should be easily accelerated to the velocity of sound, and the subsequent growth of their velocity should be limited by the aforementioned mechanism. It is therefore of interest to examine the factors that can accelerate the drops effectively. These may be electric and magnetic fields, as well as inhomogeneous deformations. The most effective is the latter mechanism, which will be considered here in detail.

Assume that a tension field $\sigma_{ik}(\vec{r})$ is produced in the crystal, and let the energy per particle in the drop E_d (as well as the total energy in the system) be dependent on σ. Then a drop situated at the point $\vec{r}$ is acted upon by a force

$$F_i = -(N \operatorname{grad} E_d(\sigma))_i = -N \frac{\partial E_d}{\partial \sigma_{ik}} \frac{\partial \sigma_{ik}}{\partial r_i}$$

(N is the number of particles in the drop), and the drop will acquire during the free-path time τ a velocity

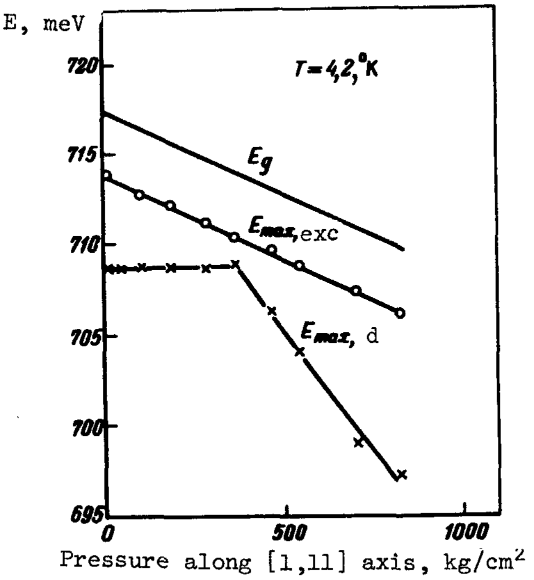

Fig. 1. Dependence of width of forbidden band (E_g), exciton-radiation energy, and electron-hole radiation energy on the uniaxial compression.

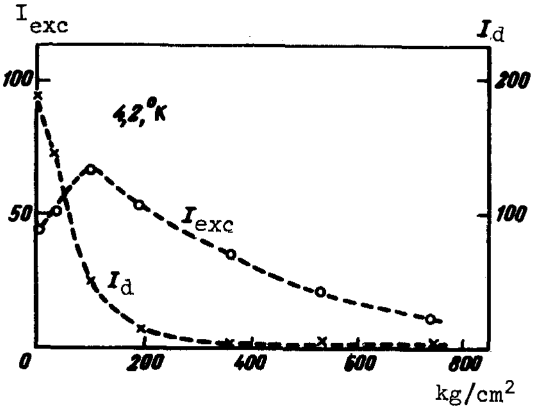

Fig. 2. Dependence of the radiation intensito of the free exciton and of the electron-hole drops on the compression. Ordinates: left - scale for exciton line intensity, right - scale for EH-drop radiation intensity, in relative units.

$$\frac{\partial E}{\partial \sigma_{ik}} \frac{\partial \sigma_{ik}}{\partial \mathbf{r}} \frac{\tau}{m},$$

where m is the exciton mass. Assuming $\partial E/\partial \sigma \simeq 10^{-5}$ eV/cm^2, $\tau \sim 10^{-6}$ sec, and $m \sim 10^{-27}$ we find that the particle is accelerated to the velocity of sound at a spatial stress change of 10 kg/cm^2 in a length of 1 cm.

We have performed experiments on recombination radiation under conditions of unilateral compression. The investigations were made on n-Ge single crystals with residual impurity density 5×10^{11} cm^{-3}. The excitation source was an He-Ne laser with emission wavelength 1.15 μ. The source produced a light flux of about 10^{17} phot/sec. The spot diameter was ~ 300 μ. The measurements were made at temperatures 2 and 4°K. The photoluminescence spectrum revealed, besides the radiation of the free exciton (E_{max} = 713.8 meV), also the emission line of the EH drops with E_{max} = 709.6 meV [3].

The main results of the measurements, shown in Figs. 1 and 2, reduce to the following: 1. In the pressure interval 0 - 350 kg/cm^2, the emission line of the EH drops is hardly shifted by the pressure, in contrast to the exciton line. 2. In the region $P > 350$ kg/cm^2 the value of E_d shifts towards the long wave region more rapidly than E_h and E_{exc}, which shift, as before, almost parallel to each other, at the same slope as at pressures below 350 kg/cm^2. 3. The drop radiation intensity decreases catastrophically in the entire investigated pressure range (a drop by a factor 10 - 150 for different samples and experimental geometries), while the intensity of the exciton line first increases somewhat and then decreases, but much more slowly than the emission of the drops.

The result (1) is due to the decrease of the particle binding energy in the drop, a decrease connected with the change of the structure of the germanium conduction band following uniaxial deformation along the [111] axis. In such a deformation, one of the four equivalent minima of the conduction band drops, and electrons are transferred from it to the other minima. The Fermi energy and the electron pressure are increased thereby, and this should lead to a broadening of the drop, i.e., to a decrease of the equilibrium density of the particles and to a decrease of the binding energy per particle pair, since the average distance between particles increases. In other words, the drop and exciton lines should come closer together with increasing deformation, as is indeed observed. This approach, however, shoudl stop after all the electrons have been transferred to one minimum, i.e., when the distance between minima exceeds the Fermi energy, as is likewise in qualitative agreement with Fig. 1. A pressure 300 kg/cm^2 corresponds to $\Delta E_h \sim 3$ meV, which is close in order of magnitude to the Fermi energy in the drop, estimated from the emission line width and from the equilibrium concentration n_0.

At higher pressure, the EH line of the drops should shift parallel to E_{exc} and E_d. At first glance, this contradicts the result (2) and (3) can be readily explained, however, as being due to the drop motion caused by the macroscopic inhomogeneity of the deformation, which is inevitable under the conditions of the described experiment. In the presence of such an inhomogeneity, the EH drops are drawn into the region of maximum deformation and their radiation emerges from a region where the deformation is certainly larger than the average value. Therefore E_d shifts more rapidly than the exciton line, the shift of which is due to the average tension in the illuminated region of the sample. This point of view is confirmed also by the fact that the slope of the $E_d(P)$ curve at $P > 350$ kg/cm^2 changes appreciably from sample to sample, and, depending on the position of the illuminated sample, from a slope almost parallel to E_{exc} to one larger by 1.5 - 2 times. It is possible to explain similarly the anomalous drop of the radiation intensity of the EH drops with increasing deformation. Being accelerated under the influence of the deformation gradient, the drops go out of the region in which they can grow (where the excitons are produced) within a time $< L_D/S \sim 10^{-6}$ sec (L_D is the exciton diffusion length and S is the speed of sound). This time is shorter than the lifetime of the drop [3, 4], and the drop cannot reach its equilibrium volume. In other words, the number of excitons condensed in the drop decreases, since the nuclei of the EH drops are continuously being drawn out from the region "saturated" with excitons as soon as they are produced. The picture is also complicated by the fact that the nuclei are produced fastest on the microinhomogeneities (there is direct experimental evidence that these microinhomogeneities are the dislocations), from which they are detached by the applied stress. It should be noted that the foregoing explanation of the decrease of the intensity of the EH drops is not valid in the pressure region < 300 kg/cm^2, if it is assumed that in this region E_d is not rigorously pressure dependent. However, the shifts of E_d needed for the acceleration are so small, that they lie completely within the limits of the measurement accuracy (± 0.5 meV).

The drop-motion hypothesis is favored also by an experiment in which radiation was registered from a small region of the sample, in which strong deformation was produced with the aid of a tungsten needle. When the excitation region was moved over the sample to a distance up to 50 mm from the needle point, the intensity of the radiation from under the needle decreased by a factor more than 2, i.e., the diffusion length of the radiating objects was ~ 1 cm, which is larger by one order of magnitude than the diffusion length of the free excitons [6]. A detailed description and discussion of these experiments will be published elsewhere.

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