Electron-hole drop motion due to mutual repulsion forces

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(Submitted July 21, 1977)
Pis'ma Zh. Eksp. Teor. Fiz. **26**, No. 5, 395–398 (5 September 1977)

Light scattering was used to investigate the kinetics of the spatial distribution of electron-hole drops (EHD) in germanium in the case of pulsed volume excitation. It is shown that there exist two stages of drop motion: "fast" motion, in which a drop cloud is produced, and "slow" motion, due to the mutual repulsion of the EHD.

PACS numbers: 71.35.+z

Much attention is being paid presently to the investigation of EHD motion produced at high excitation levels.[1–6] We have succeeded in the present study in tracing the evolution of the spatial distribution of drops in time under volume excitation, and to draw on this basis conclusions concerning the causes of EHD motion.

The source of the volume excitation was pulsed barium-vapor laser ($\lambda = 1.5$ μm, pulse duration $\tau_p \sim 20$ nsec, repetition frequency $f \sim 3$–4 kHz). The exciting radiation was focused on the front surface of the sample into a spot of ~300 μm diameter. By the same token, the nonequilibrium carriers were produced in a cylinder with a base diameter ~300 μm and height 3 mm (sample thickness), i.e., a cylindrical experimental geometry was realized (accurate to the inhomogeneity in the carrier distribution over the sample thickness).

The distribution of the EHD over the sample at an instant of time after the exciting pulse (temporal resolution ~0.5 μsec) was determined from the signals due to scattering or absorption of the sounding radiation of wavelength

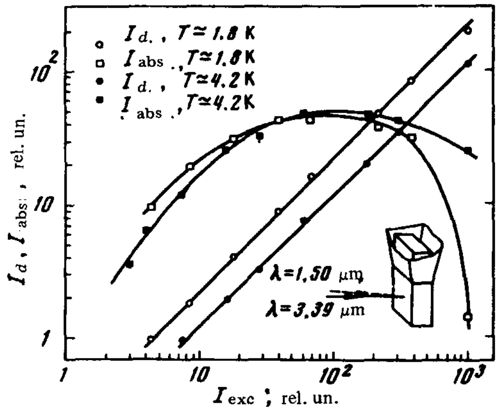

FIG. 1. Plots of the absorption signal I_{abs} and of the EHD recombination radiation intensity I_d against the excitation level J_{exc}

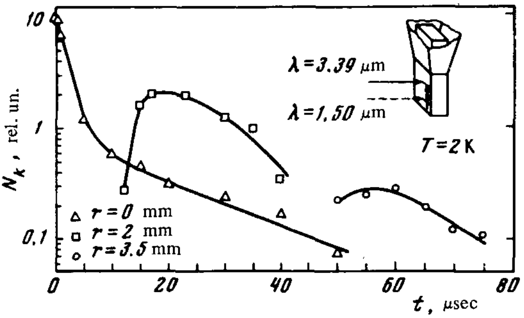

FIG. 2. Dependence of the drop concentration N_d at three points of the sample on the time t.

3.39 μm, directed parallel to the axis of the exciting cylinder. The optical system of the setup is described in greater detail in[7]. The measurements were made on mechanically polished samples of germanium with the residual-purity concentration less than 10^{12} cm^{-3}.

Figure 1 shows plots of the absorption (sounding-beam diameter ~ 1 mm) and of the integrated intensity of the EHD recombination radiation against the excitation level at temperatures $T = 1.7$ and 4.2 K. In this experiment, the exciting and sounding beams were congruent ($r = 0$) and the measurements were performed 2 μsec after application of the exciting pulse. It is clear from Fig. 1 that the integrated (over the volume of the samples) recombination-radiation intensity increases linearly with the excitation level, whereas the absorption signal begins to decrease sharply with increasing excitation intensity. This behavior of the absorption signal can be attributed to departure of the drops from the sounding beam. When the temperature is lowered, the drop mobility increases, and therefore also their velocity, so that the decrease of the absorption becomes steeper.

The dependence of the drop concentration at three points of the sample (spatial resolution ~ 300 μm) on the time is shown in Fig. 2. The drop concentration was calculated from the scattering signal without allowance for the EHD size distribution.[8] As seen from Fig. 2, at each instant of time the EHD are concentrated mainly in a narrow cylindrical layer whose average radius increases gradually.[1)] At the beginning, the radius of the cylindrical layer increases quite rapidly, but subsequently the motion of the drop cloud is substantially slowed down. For example, as follows from our experiment, the rate of change of the outer radius of the layer at 0.5 μsec following the action of the exciting pulse is ~ 10^5 cm/sec, and decreases sharply during the first 10 μsec. This is followed by a relatively slow phase of drop-cloud motion, characterized by average velocities ~ 3×10^3 cm/sec (from $r = 2$ mm to $r = 3.5$ mm) and by a relatively weak decrease of the instantaneous velocity.

Phonon-wind theory[2,3] cannot explain the formation of the cylindrical EHD layer if the initial drop distribution was previously homogeneous. It is most probable that this effect, as well as the "fast" phase of the motion, is due to the onset of a powerful mechanism of phonon generation at high concentrations of the nonequilibrium carriers. This mechanism attenuates relatively rapidly, as indicated by the sharp decreases of the instantaneous velocity of the leading front of the drop cloud during the first 10 microseconds. However, the mechanism that produces these phonons and the state of the carriers that emit them are presently unclear.

The subsequent "slow" motion of the layer is the result of the mutual EHD repulsion due to generation of phonons by the drops themselves.[2,3] In this case the change of the outer radius of the cylindrical layer as a function of the time is given by[3]

$$r(t) = r(t_o)\left\{1 + \frac{4\tau_o\tau_P}{n_o^2 m^* r^2(t_o)}\rho^2 N_\epsilon(t_o)\left[1 - \exp\left(-\frac{t - t_o}{\tau_o}\right)\right]\right\}^{1/2},$$

where τ_0 is the carrier lifetime in the liquid phase, n_0 is their density, τ_r is the carrier momentum relaxation time in the EHD, m^* is the effective mass of the electron-hole pair, ρ is the constant of the repulsion interaction, the explicit form of which is given in[3], [2)] and $N_\Sigma(t_0)$ is the number of carriers in the liquid phase per unit length of the cylinder. Let us estimate ρ by using this expression. At

$$\tau_o = 40\ \mu\text{sec},\ \tau_P = 2\cdot 10^{-8}\ \text{sec},$$
$$n_o = 2\cdot 10^{17}\ \text{cm}^{-3},\ m^* = 0.4\, m_o,\ t = 12\ \mu\text{sec},\ t = 50\ \mu\text{sec},\ r(t_o) = 2\ \text{mm},\ r(t) = 3.5\ \text{mm},$$

and $N_\Sigma(t_0) \approx 6\times 10^{13}$ cm^{-1} we obtain $\rho \approx 100$ g$^{1/2}$ cm$^{-3/2}$ sec^{-1}. The difference between this value and that determined in[4] can be attributed to the fact that the drop motion was not separated in[4] into fast and slow phases. A similar remark pertains also to[5,6] where the fast motion occurred in fact.

In conclusion, we wish to thank V. S. Bagaev and L. V. Keldysh for constant interest and useful discussions, V. D. Kopylovskiĭ for help with constructing the electronic apparatus, and N. V. Zamkovets for help with the experiments.

[1)] The formation of an EHD layer was first observed in[1] and was not satisfactorily explained up to now.

[2)] In our earlier paper[2] we considered two mechanisms whereby nonequilibrium phonons interact with EHD: phonon absorption and phonon scattering. It appears that the "phonon wind" is determined principally by the process of absorption of long-wave phonons, and the theoretical estimate we present in[2] for the scattering probability of short-wave phonons is much too high.

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