Formation of a layer of electron-hole drops with the expansion of a cloud of nonequilibrium charge carriers with transonic velocity

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It is found that in the initial stage of the evolution of a cloud of nonequilibrium charge carriers, created by a short pulse of light in Ge, the leading edge of the cloud moves with transonic velocity, almost independent of temperature and intensity of excitation. It is shown that the basic experimental data can be explained by taking into account the delay between the emission and absorption of nonequilibrium phonons.

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Under pulsed excitation of germanium, a layer of electron-hole drops (EHD), which moves into the bulk of the crystal, is formed.[1] It was established in Refs. 2–4 that the EHD layer is formed within a time $t \lesssim 1\ \mu s$, while its subsequent motion is due to dragging of the drops by the phonon wind.[1),5,6] However, the reasons for the formation of the EHD layer remain unclear, although some possibilities were examined in Refs. 8 and 9. The mechanisms proposed in these papers, however, cannot explain all of the experimental data.

In this paper, we present the results of investigations of the initial stage of the kinetics of the cloud of nonequilibrium carriers over times $t \lesssim 1\ \mu s$, i.e., when EHD are created and grow during the formation of the layer. The data obtained are discussed on the basis of the model of dragging of nonequilibrium carriers by phonons taking into account the delay arising due to the finiteness of the velocity of sound. The model examined permits explaining the formation of the EHD layer, as well as a number of previously not understood experimental results.

The experiments were performed on mechanically polished specimens with pure germanium. A specimen was excited with a molecular nitrogen laser (wavelength $\cong 0.34\ \mu m$, pulse duration $\cong 10$ ns, maximum pulse energy $\cong 120$ erg). The laser beam was focused on a spot with dimensions 3×4 mm on the lateral surface of the specimen (Fig. 1a), so that the geometry of the experiment may be assumed to be planar, and the motion of the drops is one-dimensional. We measured the spatial distribution of the absorption of the probing radiation at 3.39 μm by nonequilibrium charge carriers at different times after the excitation pulse. The experimental procedure is described in greater detail in Ref. 4.

The dependences of the velocity of the leading edge of the cloud of nonequilibrium carriers on the distance x to the excited surface of the specimen, obtained under different experimental conditions, are shown in Fig. 1. It is evident that for small x there is a section on which the leading edge of the cloud moves with constant velocity

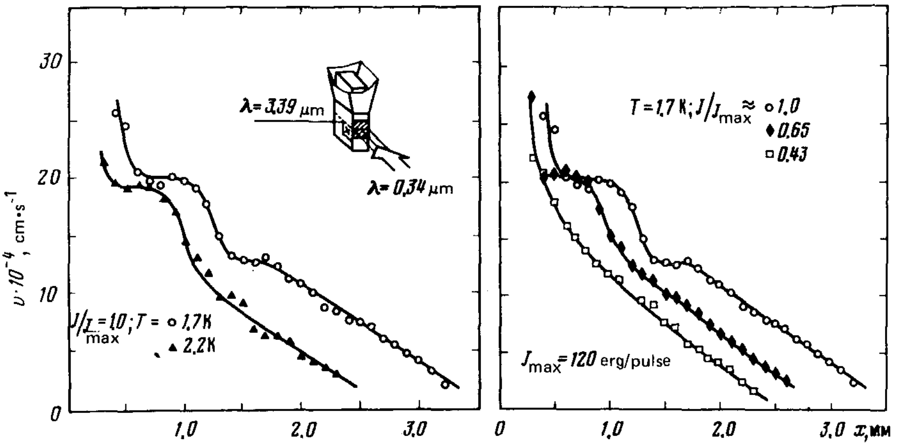

FIG. 1. Experimental dependences of the velocity of the leading edge of the cloud of nonequilibriuim charge carriers on the distance to the excited surface of the specimen for different temperatures (*a*) and pumping levels (*b*). The x axis is oriented along $\langle 100 \rangle$.

$\cong 2 \times 10^5$ cm/s, close to the velocity of transverse sound. The velocity at this stage of evolution of the cloud is almost independent of the intensity of excitation and temperature, but, as the temperature decreases and the level of excitation increases, the duration of the motion with constant velocity increases. At low pumping levels, the expansion of the cloud with constant velocity does not occur (Fig. 1b). The stage of the kinetics of the cloud described above terminates with a sharp deceleration of the leading edge of the cloud to velocities corresponding to the motion of the EHD layer under the action of the phonon wind emitted by the "hot spot," (Refs. 7, 10, and 11) and this mechanism for generating phonons is reponsible for the further motion of the layer (linear section on the v vs x curve).[4,7]

We shall now discuss the experimental data in terms of the following model: an infinite plane layer with thickness a, uniformly filled with nonequilibrium carriers with density n, is created initially in an infinite isotropic crystal. Simultaneously, some number (proportional to n) of ballistic phonons, interacting efficiently with carriers and EHD, is liberated in this layer. We shall place the origin of coordinates at the center of the layer and orient the x axis perpendicular to the surfaces bounding the layer. Taking into account the retardation, the phonon energy flux density at the point r at the time t is

$$\mathbf{w}(\mathbf{r}, t) = \frac{\Delta E}{4\pi} \int n \delta\left(t - \frac{|\mathbf{r} - \mathbf{r}'|}{s}\right) \frac{\mathbf{r} - \mathbf{r}'}{|\mathbf{r} - \mathbf{r}'|^3} d\mathbf{r}', \tag{1}$$

where ΔE is the energy converted into ballistic phonons for each electron-hole pair created, and s is the velocity of sound. When the phonons are absorbed by carriers, a force $\mathbf{f} = \sigma \mathbf{w}/s$ acts on the carriers and they acquire a velocity $\mathbf{v} = \mu \mathbf{f}$, where σ is the average phonon absorption cross section and μ is the carrier mobility (the equations for calculating f are presented in Refs. 5–7). In dimensionless units ($V = v/s$, $X = 2x/a$, $\tau = 2st/a$), the equation of motion of carriers has the form (for $X > 0$)

$$\frac{dX}{d\tau} = \min\{1, V(X,\tau)\}, \tag{2}$$

where

$$V(X,\tau) = \begin{cases} 0, & \tau < |X-1|, \quad \text{region I} \\ V_0\left[1 - \frac{(X-1)^2}{\tau^2}\right], & |X-1| < \tau < X+1, \quad \text{region II} \\ 4V_0X/\tau^2, & \tau > X+1, \quad \text{region III} \end{cases} \tag{3}$$

and $V_0 = \mu\sigma\Delta En/4s$ is a parameter that characterizes the magnitude of the dragging of carriers by the phonon wind. It increases with increasing pumping level (n increases) and with decreasing temperature (μ increases). The derivation of (2) taken into account the fact that the phonon wind cannot accelerate the carriers to supersonic velocity.

Equation (2) can be solved analytically. We shall not write out the solution, but we shall present the results in graphical form.[2)] Typical families of carrier trajectories are illustrated in Fig. 2. For large V_0, the trajectories bunch up near the leading edge of the cloud, i.e., the carrier density increases at the leading edge. It can be shown that near the leading edge of the cloud the density diverges as

$$\frac{n(X,\tau)}{n} \propto \frac{\tau^2}{[X_f(\tau) - X(\tau)]^{(1 - 1/\sqrt{1+4V_0^2})}}, \tag{4}$$

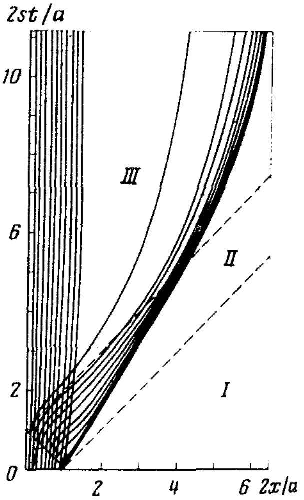

FIG. 2. Family of carrier trajectories for $V_0 = 0.1$ (almost vertical lines) and $V_0 = 1$. The dashed lines represent the boundaries of the regions I, II, and III [Eq. (3)].

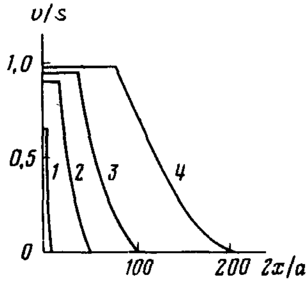

FIG. 3. Velocities of the leading edge of a planar cloud of nonequilibrium carriers as a function of distance to the center of the cloud (calculation). The section $v/s = \text{const}$ is the solution in region II; the drop is in region III; $V_0 = 1$ (1), 5 (2), 10 (3), and 20 (4).

where $X_f(\tau)$ is the coordinate of the edge. A dense layer of carriers forms because the carriers behind the leading edge move under the action of a large force [see (3)] and catch up with the leading edge of the cloud. In addition, for $V_0 > 1$, there are regions of total entrainment ($V = 1$) behind the front. If retardation is ignored, the velocity of the carriers increases from the center of the cloud to its boundaries. Of course, carrier diffusion will wash out the front and eliminate the divergence in (4).

The dependences of the velocity of the leading edge on its coordinates are shown in Fig. 3. For $V_0 \ll 1$, $V_f \propto V_0$, while for $V_0 \gg 1$, $V_f \propto (1 - 1/2V_0)$. Comparison of Figs. 3 and 1 shows that this model agrees well with experiment.

If retardation is taken into account, we can explain not only the formation of the layer but also the superlinear increase in the total number of nonequilibrium carriers in the bulk of the specimen with increasing intensity of surface pumping, which was observed in Ref. 4 and which is directly evident in Fig. 2. We can also explain some other experimental data presented in Ref. 3.

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[1)] A review of papers on the effect of the phonon wind on the spatial distribution and other properties of EHD is included in Ref. 7.

[2)] The results of detailed calculations will be published separately by S. G. Tikhodeev.

[1] T. C. Damen and J. M. Worlock, Proc. Third Int. Conf. on Light Scattering in Solids, Camping, Brazil, 1975 (Flammarion, Paris, 1976), p. 183.

[2] A. D. Durandin, N. N. Sibel'din, V. B. Stopachinskiĭ, and V. A. Tsvetkov, Pis'ma Zh. Eksp. Teor. Fiz. **26**, 395 (1977) [JETP Lett. **26**, 272 (1977)].

[3] I. V. Kavetskaya, N. N. Sibel'din, V. B. Stopachinskiĭ, and V. A. Tsvetkov, Fiz. Tverd. Tela **20**, 3608 (1978) [Sov. Phys. Solid State **20**, 2085 (1978)].

[4] N. V. Zamkovets, N. N. Sibel'din, V. B. Stopachinskiĭ, and V. A. Tsvetkov, Zh. Eksp. Teor. Fiz. **74**, 1147 (1978) [Sov. Phys. JETP **47**, 603 (1978)].

[5] V. S. Bagaev, L. V. Keldysh, N. N. Sibel'din, and V. A. Tsvetkov, Zh. Eksp. Teor. Fiz. **70**, 702 (1976) [Sov. Phys. JETP **43**, 362 (1976)].

[6] L. V. Keldysh, Pis'ma Zh. Eksp. Teor. Fiz. **23**, 100 (1976) [JETP Lett. **23**, 86 (1976)].

[7] V. S. Bagaev, T. I. Galkina, and N. N. Sibeldin, in: Electron-Hole Droplets in Semiconductors, Ed. by C.

D. Jeffries and L. V. Keldysh, North-Holland, 1983, Chap. 4.

[8] R. S. Markiewicz, Phys. Rev. B. **21**, 4674 (1980).

[9] B. M. Ashkinadze, Author's Abstract of Doctoral Dissertation, A. F. Ioffe LFTI, Akad. Nauk SSSR, Leningrad, 1981.

[10] J. C. Hensel and R. C. Dynes, Phys. Rev. Lett. **39**, 969 (1977).

[11] D. V. Kazakovtsev and I. B. Levinson, Pis'ma Zh. Eksp. Teor. Fiz. **27**, 194 (1978) [JETP Lett. **27**, 181 (1978)].

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