Electron-hole drops and the appearance of a strong plasma in Ge at a high level of optical excitation

B. M. Ashkinadze and I. M. Fishman

A. F. Ioffe Physicotechnical Institute, USSR Academy of Sciences

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At a high level of excitation of germanium, regions were observed of a dense electron-hole plasma, accompanied by the appearance of fast kinetics of the decrease of the recombination radiation of the electron-hole drops. These results are explained as being the consequence of the effect of the dispersal of the drops when a certain threshold excitation level is reached, when the kinetic energy of the rapidly moving drops turns out to be sufficient to break up the drop by inelastic impact and produce a cluster of dense plasma.

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It was observed in investigations of the microwave conductivity of optically excited germanium at $T \leq 4.2\,^\circ\mathrm{K}$[1,2] that regions occupied by clusters of a dense electron-hole plasma appear in the sample in the case of sufficiently strong pumping. The properties of these plasma clusters, and primarily their density, turned out to be quite different from the properties of the electron-hole drops (EHD). The hypothesis was advanced that in stationary excitations, the clusters of the dense plasma can arise as a result of a phase transition in the dense gas of electrons and holes, which exists near the surface of the sample. We present here the results of an investigation of the kinetics of a dense plasma and the recombination radiation of EHD, which offer evidence that in order for plasma clusters to appear in the sample it is necessary to produce a sufficiently large amount of the condensed phase; by the same token, the process that leads to formation of the dense plasma is apparently different from that proposed in[2].

The experimental procedure is described in[2,3]. The germanium sample was placed in the waveguide of an 8-mm band microwave line. Pulsed excitation was effected with a GaAs laser of power 10 W at a pulse duration from 0.2 to 10 μsec. A homodyne microwave spectrometer was used, so that is was possible to register separately the absorption and dispersion signals.

Oscillograms of the signals of the recombination radiation of the EHD, of the microwave absorption, and of the dispersion, corresponding to two excitation levels, are shown in Fig. 1. At a pump intensity I less than a certain threshold value I_{thr}, the radiation pulse attenuates exponentially with $\tau_0 \sim 35$ μsec; the microwave absorption stops after the end of the excitation pulse. In the dispersion signal there is a positive component which also decreases with $\tau_0 \sim 35$ μsec; this component is due to the presence of EHD in the sample,[2] and the amplitude of the signal is proportional to the volume of the liquid phase. At $I > I_{\mathrm{thr}}$, an appreciable microwave absorption, which fluctuates strongly with time, is produced in the form of irregular sharp spikes of dura-

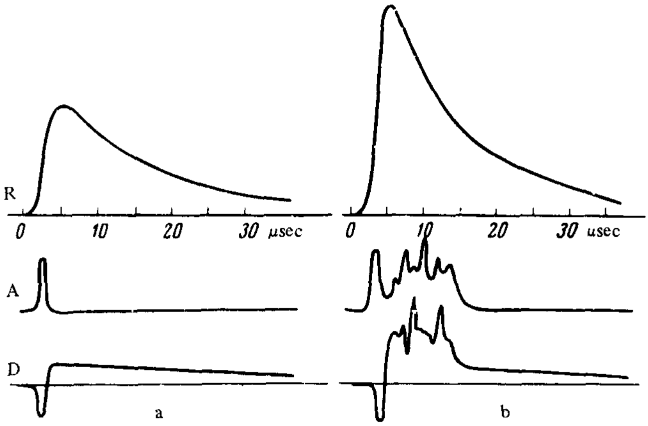

FIG. 1. Oscillograms of signals of the recombination radiation (R), microwave absorption (A), and microwave dispersion (D) at excitation intensities (in relative units): a—10, b—20.

tion ~50 nsec (the duration of an individual spike is determined by the time resolution of the apparatus); the dispersion signal also increases strongly and fluctuates. In the same pump region, the recombination radiation pulse is gradually deformed; a fast component is produced, meaning that the greater part of the drops vanishes much more rapidly that in the case of weak pumping1).[3]

An investigation of the microwave conductivity at $I > I_{\text{thr}}$[3] leads to the conclusion that this conductivity is due to plasma clusters with density $\sim 10^{16}$ cm^{-3} which are localized in space. To ascertin how the plasma clusters are produced (whether their threshold is determined by the rate of the generation or by the total number of nonequilibrium carriers), we investigated the dependence of this threshold on the excitation conditions.

By varying the amplitude or duration, and also by exciting the sample with a sawtooth light pulse with a rise time ~20 μsec, we have verified that in order for the plasma clusters to be produced it is necessary that the total number of the nonequilibrium carriers introduced into the sample exceed a certain critical value, corresponding to a density $\sim 2 \times 10^{15}$ cm^{-3} when averaged over the sample. In the case of a long excitation pulse (Fig. 2), the plasma is produced at the instant of time when the threshold pair concentration is reached in the sample. An increase of the intensity causes the plasma to appear earlier. Inasmuch as at low temperatures almost all the carriers are rapidly bound into EHD, an increase of the pump-pulse duration should lead only to an increase of the volume of the liquid phase. Thus, when the total volume of the EHD reaches ~1% of the excited volume of the crystal, clusters of dense plasma are produced, and the lifetimes of certain drops decrease.

Another essential feature of the kinetics of a dense plasma is the fact that in the case of a short excitation pulse, but not of sufficient power, the plasma can be produced either immediately after the pulse, or with a certain delay,

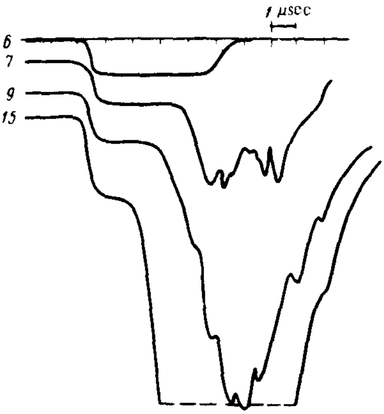

FIG. 2. Oscillograms of microwave absorption signals at a laser-light duration 5 μsec; the numbers alongside the pulses indicate the excitation intensity (in relative units).

which is sometimes appreciable (Fig. 1). The latter may mean that the source of the energy needed for the production of the plasma is the recombination into EHD.

In our opinion, the phenomenon described above should be regarded as a consequence of rapid motion of drops of the electron-hole liquid. As shown in[5], in the case of sufficiently strong pulse excitation, a cloud of minute electron-hole drops is produced near the surface of the sample, and these drops travel into the interior with large initial velocity (it should be noted that the mechanism of the dispersal of the drops is still not clear, although certain models describing the dispersal are given in[6,7]). If it is assumed[5] that the velocity of motion of the drops increases with increasing excitation level and reaches a value $\sim 3\times10^6$ cm/sec, then a sufficient kinetic energy may be stored in the drop so that when the drop collides inelastically with the sample surface, with a defect, or finally with another drop, the impinging drop becomes heated to $T \gtrsim T_{cr}$, where T_{cr} is the critical condensation temperature.[2)] The drop will then explode, and a cluster of dense plasma will be produced; the latter, after cooling, will again turn into a drop.

In the considered picture it is necessary to have high-velocity drops moving in the crystal during an appreciable time after the end of the pump pulse. This can be explained by assuming that both the dispersal of the drops and their subsequent motion in the bounded sample are due to phonon wind.[6,8] Indeed, the threshold of the phenomenon becomes lower when the sample dimensions are limited, and it becomes possible for an appreciable concentration of rapidly moving drops to be accumulated.

Thus, the appearance of a dense plasma in a "cold" sample can be explained by taking into consideration the effect of motion of the drops with large velocities; the question of whether the observed plasma clusters correspond to a new metastable phase state of the system must be regarded as still open; some arguments favoring this assumption are given in[3].

In conclusion, we mention certain mechanisms that can give rise in principle to clusters of dense plasma not as a result of concentration of the drops and their dispersal, but as a result of the increase of the drop and its reaching a certain critical dimension with increasing pump.

1. Accumulation of excitons in the space between the drops and a plasma phase transition in thee xciton-electron gas at $T \ll T_{cr}$.[9] The accumulation of excitons can be attributed to the growth of the drop radius, and also to the reaching of the maximum radius determined by the phonon wind.[8]

2. Explosion of a drop that has reached a critical dimension, and its conversion into a plasma cluster. The explosion may be due to the accumulation of phonons emitted in the course of recombination.

These last mechanisms for the appearance of a dense plasma should be accompanied either by the deformation of the EHD emission spectra, or by an appreciable change in the radius of the drops, or finally by the appearance of excitons in the spectrum when the pump exceeds the threshold. These phenomena, however, have not yet been observed in experiment.[3,5]

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[1] The recombination radiation spectra of the EHD were deformed neither when the excitation level was changed nor when they were recorded with different delays relative to the pump pulse, and corresponded exactly to the spectra obtained in[4]. A more detailed investigation of the kinetics of the radiation is given in[3].

[2] We note that in this case the number of "hot" drops with $T \lesssim T_{cr}$ in the crystal will be quite small, since the energy is released in the drop rapidly, and if the drop has not evaporated, then it cools off within $\sim 10^{-8}$ sec.

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