Action of thermal pulses on the radiation of electron-hole droplets in germanium

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A rapid quenching of the recombination radiation of the droplets, accompanying the appearance of a dense plasma in the material, was observed when a stream of phonons, generated by a thermal contact, acts on a system of electron-hole droplets (EHD's) in germanium. It is shown that these effects are caused by the removal of the droplets to the surface of the material and their destruction there.

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It was shown in Refs. 1 and 2, that electron-hole droplets (EHD's) in germanium can be entrained by a stream of nonequilibrium phonons. The droplet movement that occurs in this case leads to a number of unique features in the behavior of the EHD system.[3,4] We have discovered a new phenomenon in our work—a quenching of the recombination radiation of the EHD by the stream of phonons that accompanies the appearance of a dense plasma of free carriers in the crystal.

A stream of nonequilibrium phonons, entraining the droplets, was created by means of thermal pulses.[5,6] As is well known, the entrainment force is determined by the absorption in the droplets of long-wavelength phonons with $q \approx k_F$ and is proportional to the intensity of the phonon stream,[1,2,6,7] with these phonons propagating ballistically in the crystal. In view of this, the generation of phonons by means of

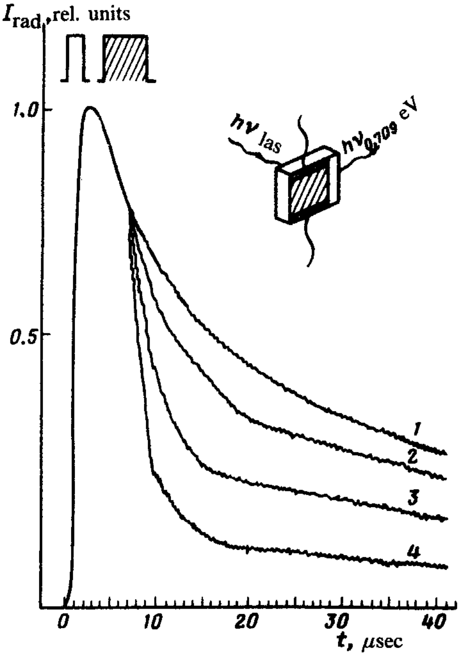

FIG. 1. Radiation kinetics of EHD's in germanium acted upon by thermal pulses with a duration of 5 μsec and different powers P, W/cm^2: 1—0; 2—0.76; 3—3.9; 4—8.05. Oscillograms of the excitation and thermal pulses are shown in the upper portion of the figure.

thermal pulses is a convenient method of studying both the droplet motion process itself and the phenomena accompanying it, since in this case one can easily control the amount of force applied to the droplets and the time during which it acts.

The experimental set-up is shown in the inset in Fig. 1. Germanium samples ($N_i \approx 3 \times 10^{10} - 10^{13}$ cm^{-3}) with dimensions of $2 \times 4 \times (4-6)$ mm^3 were investigated. A thermal contact was applied to one face of these samples. Droplets were excited from the opposite crystal face by a light flash of a GaAs laser with a pulse length 1 –2 μsec. Before the application of the thermal contact the sample was polished and etched; then an insulating TiO_2 film was deposited by the cathode sputtering method. The thermal contact was prepared by the evaporation of a Constantan film with dimensions of 2×3 mm, which had a resistance of ≈50 ohms. Rectangular voltage pulses with amplitude up to 20 V and with an adjustable delay time relative to the excitation flash were applied to the film. The relaxation of the EHD recombination radiation and the microwave conductivity of the sample were studied.[4] The radiation of the droplets was detected with a germanium photodiode; the photodetector time constant was 2×10^{-7} sec. The sample was placed in liquid helium at $T = 1.8$ K.

It is seen from Fig. 1 that the action of the phonon stream, created by a thermal pulse with a 5-μsec duration, on the EHD system leads to a rapid decay in the droplet radiation. The effect exhibits a threshold that appears when the thermal pulse power reaches a value of $P_{thr} = 4$ W/cm^2. This is demonstrated in Fig. 2, which shows the dependence on power of the EHD radiation signal after the action of a thermal pulse.

In Ref. 8, where the entrainment of EHD's in germanium by phonons generated by thermal pulses was investigated directly, it was found that this value P_{thr} corre-

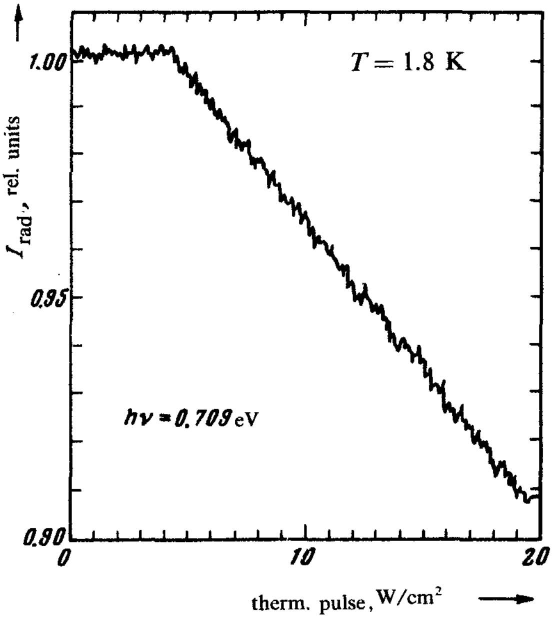

FIG. 2. Dependence of the EHD radiation intensity after completion of thermal pulse on its power. Thermal pulses with a duration of 5 μsec were applied with a delay of 7 μsec relative to the excitation pulse, and the radiation was detected after 29 μsec.

sponds to the start of droplet movement. The existence of a threshold for EHD movement was discovered in Refs. 9, 10 and was related to the retention of the droplets at crystal defects.[8,10,11] In order to strip the droplets from the trapping centers it is necessary to apply a force to the particle pair in the droplet that exceeds a value of ≈ 1 meV/cm.[8,10] In this way radiation quenching occurs when the droplets start to move due to the action of the phonon stream.1) The cause of this effect is apparently the removal of the droplets to the sample surface.

Figure 3 shows an oscillogram of the EHD radiation signal during the action of short thermal pulses when three regions are clearly visible in the radiation kinetics. The first, fastest region appears with a time delay of ≈ 1 μsec with respect to the start of the thermal pulse. The ballistic transit time of the phonons from the metallic film to the excited region of the crystal does not exceed 0.4×10^{-6} sec. Consequently, the rest of the delay time is determined by the time to remove the droplets to the surface and for recombination to occur in them.

Let us assume that the initial droplet distribution in the sample is uniform with an average density N_0. Assuming that the lifetime τ_0 of the electron-hole pairs in a droplet, located within the volume of a sample with a thickness d, is much longer than the lifetime τ_n of a drop found at the surface, one can easily obtain the following approximate expression for the initial relaxation of the EHD radiation during the action of a thermal pulse that causes them to move toward the surface with a velocity v

$$I \approx I_0 e^{-t/\tau_0}\left(1 - \frac{vt}{d} + \frac{vt}{d} e^{-t/\tau_n}\right). \tag{1}$$

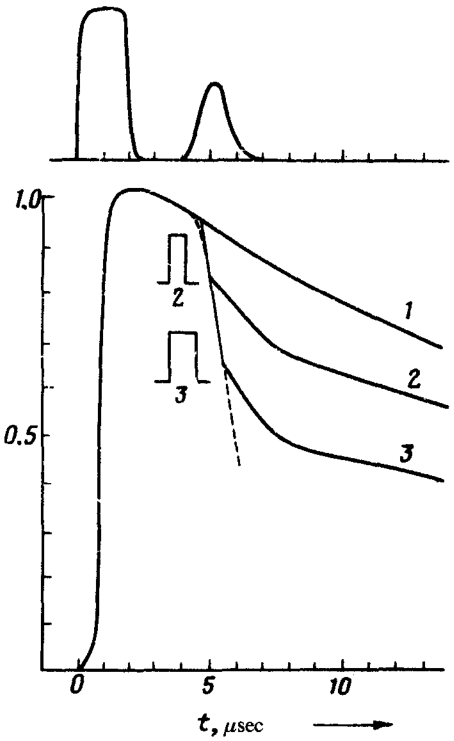

FIG. 3. Radiation kinetics of EHD's in the absence (1) and during the action of thermal pulses with a power of 80 W/cm^2 and a duration t_p of: 2—0.6 μsec, 3—1 μsec. The dashed line shows the decay kinetics calculated from Eq. (1). An oscillogram of the microwave conductivity for $t_p = 1$ μsec is shown in the upper portion of the figure. The first microwave conductivity pulse corresponds to the light excitation.

As seen from this expression, for $t < \tau_n$ and $I \approx I_0$ the decay of the radiation starts with a delay of the order of τ_n. For $t > \tau_n$ the radiation decay kinetics are determined by the magnitude of the droplet velocity. The relationship (1) is shown by the dashed line in Fig. 3 for $\tau_n \approx 0.5 \times 10^{-6}$ sec and $v = 6 \times 10^4$ cm/sec. The velocity value obtained agrees with the data of Ref. 8. The value of τ_n for a droplet, held to the surface, can be estimated from the expression $\tau_n \approx R/s$ (where R is the droplet radius and s is the surface recombination rate); hence, for $R \approx 10^{-4}$ cm, $s \approx 200$ cm/sec and $d = 0.2$ cm we obtain $\tau_n \approx 0.5 \times 10^{-6}$ sec, in agreement with experiment.

The second region of radiation decay, lasting for ≈ 3 μsec, apparently reflects the contribution of surface recombination to the radiation relaxation of droplets located near the sample surface after the action of the thermal pulse has ceased. Drops that remain in the volume determine the third decay region with a time constant $\tau_0 \approx 30$ μsec.

The microwave conductivity of the sample was investigated simultaneously with the EHD radiation kinetics, using the method described in Ref. 4. As seen from Fig. 3, the rapid quenching of the radiative recombination of the drops is accompanied by the appearance of a microwave conductivity pulse in the sample. The microwave conductivity also exhibits a threshold, coinciding with the threshold in Fig. 2. This means that the microwave conductivity is caused by the removal of EHD's to the crystal surface and by the appearance of a dense plasma near it as the result of the decay of the droplets.

Let us note that the threhold response in the microwave conductivity produced by the radiation decay is also observed at high excitation levels when the droplets start to move due to the action of the inherent phonon wind.[4]

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[1)] An abrupt decay in the drop radiation kinetics was observed in Ref. 12 with the application of a high-power SHF radiation pulse, causing a heating of electrons and, consequently, intense phonon streams.

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