Microwave absorption in a layer of electron-hole liquid on the surface of a germanium crystal

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The absorption of microwave radiation as a result of the emergence of drops on the surface of a crystal has been detected. It is shown that the effect is associated with the formation of an electron-hole liquid on the surface, which, unlike EHD, absorbs microwave radiation strongly.

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A surprising effect—the appearance of large and strongly fluctuating surges of microwave absorption that follow some period of time after illumination of germanium crystals with a sufficiently high-power light flash at temperatures below 6 K—was observed in Ref. 1. Since the condensation of excitons into drops of electron-hole liquid (EHL) occurs under similar experimental conditions, it was reasonable to attribute the observed absorption anomalies to the appearance of electron-hole drops (EHD) in the sample.

It was difficult, however, to explain the "anomalous" microwave conductivity effect by microwave absorption in the normal drops,[2–4] since the absorption cross section of the EHD is extremely small. It is assumed that at high pumping levels dense-plasma regions appear in a threshold manner. The large absorption of microwaves was attributed to the short relaxation time of the carrier pulse in these regions ($\tau_c \sim 10^{-12}$ sec).[1,4,5] The nature of these regions remained unclear.

In the present paper we explain the nature of the "anomalous" microwave absorption and show that it is caused by the formation of "puddles"—an EHL layer on the crystal surface—under certain conditions.

The microwave absorption by the electron-hole liquid increases sharply as a result of formation of the layer. The small microwave electric-dipole absorption by the drops is due to a large decrease of the electric-field intensity of the wave in the drop and to the high mobility of Fermi-degenerate carriers in it.[2–4] An EHL layer that is oriented parallel to the electric-field vector of the wave has no screening effect, and strong scattering of the carriers at the surface reduces their mobility drastically.[6] It is easy to show that in the case of formation of a continuous EHL layer the ratio of the absorption coefficients of the EHL layer and of a drop in the crystal with a total volume equal to that of the layer has the form

$$\frac{a_c}{a_{\mathrm{EHD}}} = \frac{1}{9}\,\frac{\omega_p^4}{\omega^4}\,\frac{\omega^2\tau_c\,\tau_k}{1+\omega^2\tau_c^2} \qquad (1)$$

$\omega_p = 2 \times 10^{13}$ sec^{-1} is the plasma frequency of the carriers in the EHL, τ_k and τ_c

are the relaxation times of the carrier pulse in the EHD and in the surface EHL, respectively, and $\omega = 2.3 \times 10^{11}$ sec^{-1} is the frequency of the microwave radiation. For carriers in the EHD $\tau_k \approx 10^{-10}$ sec and $\omega\tau_k \gg 1$; the value of τ_c, which is determined by scattering at the surface, does not exceed the value $w/v_F \lesssim 10^{-11}$ sec [w is the thickness of the EHL layer, which is of the order or less than the radius of the drops (10^{-4} cm), and v_F is the Fermi velocity of the carriers in the EHD]. It follows from Eq. (1) that the microwave power absorbed by a layer can increase by a factor of $\sim 10^8$ as compared with that absorbed by drops. Therefore, a formed EHL layer manifests itself clearly as a sharp increase of the microwave-absorption signal.

The EHL layer was formed when the drops were brought out to the crystal surface by a stream of long-wave ballistic phonons produced by the thermal-pulse technique.[7,8] The experimental setup is shown in the inset of Fig. 2. The germanium samples ($N_i \approx 2 \times 10^{13}$ cm^{-3}) with dimensions of $1.5 \times 3 \times 5$ mm^3 were placed in an eight-millimeter-band waveguide; the surface to be illuminated was positioned at the center of the waveguide parallel to the wave field vector. The experiments were conducted at a temperature of 1.8 K.

Figure 1 shows oscillograms of the microwave-absorption signals that were observed under these conditions. In the absence of a thermal pulse (TP) or when its power is less than the threshold P^{**}, the absorption pulses have the well-known shape (curves 1 in Figs. 1b and 1d). At a TP power exceeding P^* the drops are separated from the impurities, set in motion, and entrained to the crystal surface. Because of the short lifetime at the surface, the intensity of the drop luminescence decays sharply[8] (Fig. 1c); the cyclotron-resonance signal also decreases, since there are fewer drops that generate free carriers.[3] At $P > P^{**} > P^*$ an "anomalously" large absorption signal appears (Figs. 1b and 1d), which is caused by the entrainment of

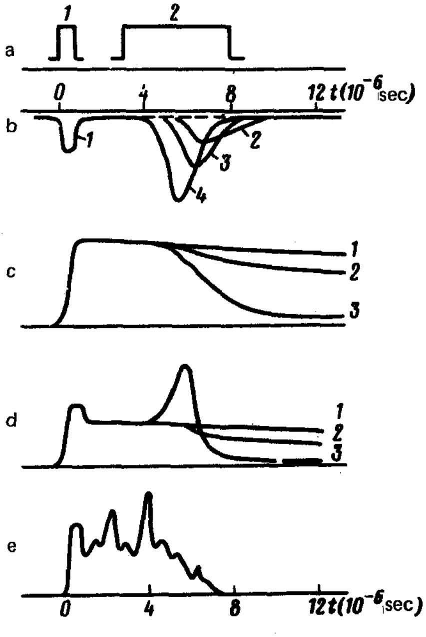

FIG. 1. Signal oscillograms of (a) 1, laser flash; 2, thermal pulse; (b) Microwave-absorption signals when the thermal-pulse power P is: 1, less than P^{**}; 2, 1.2 P^{**}; 3, 1.4 P^{**}; 4, 1.6 P^{**}; (c) luminescence signals and (d) microwave-absorption signals under electron-cyclotron-resonance conditions: 1, $P < P^*$; 2, 1.5 P^*; 3, 2.4 P^* - 1.6 P^{**}; (e) microwave-absorption signal at high pumping level ($n \approx 10^{16}$ cm^{-3}).

the drops to the surface. The magnitude and shape of this signal change little with an increase of the magnetic field to 10 kOe.

The decay of the luminescence and cyclotron-resonance signals is delayed with respect to the start of the TP by a time $T = T_{ph} + T_d + \tau_s$. Here, T_{ph} is the transit time of the ballistic phonons through the crystal, T_d is the time required for the drop to arrive at the surface, and $\tau_s \approx 5 \times 10^{-7}$ sec is the surface lifetime of the drops. The time delay of the "anomalous"-absorption pulse turned out to be dependent on the intensity of the exciting light and on the TP power; the situation can be realized when the absorption appeared almost immediately upon emergence of the drop on the surface, before the luminescence intensity started to decay. Decay of the absorption signal corresponds to a reduction in the rate of EHD entrainment either as a result of depletion of the number of drops in the volume or with termination of the phonon stream.

We noticed that the effect appears when the threshold drop density is reached at the surface. Figure 2 shows the dependence of the microwave absorption, which is induced by the photon stream, on the density $\bar{n}$ of injected pairs and on the TP power. The curves in Fig. 2a indicate the presence of an "anomalous"-absorption threshold as $\bar{n}$ varies; as the TP power (drop velocity) increases, the threshold is shifted toward lower pumping levels. On the other hand, the threshold TP power P^{**}, which is required for the appearance of the effect, decreases with increasing pumping (Fig. 2b), and at $\bar{n} \gtrsim 5 \times 10^{14}$ cm^{-3} the value of P^{**} almost coincides with the threshold P^* that determines the condition for removal of the drop from the impurity.

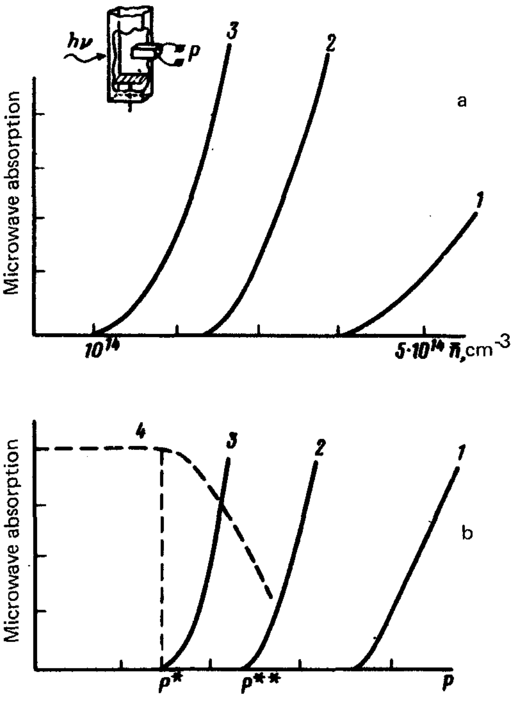

FIG. 2. Dependences of the amplitude of the microwave absorption-signal: (a) on the density of injected pairs at different power of the thermal pulse ($P_1 < P_2 < P_3$) and (b) on the TP power at different pumping levels $\bar{n}$ ($\bar{n}_1 < \bar{n}_2 < \bar{n}_3$); curve 4 represents the quenching of EHD luminescence.

The presented results show that the microwave absorption is caused by the appreciable filling of the surface with drops and by the formation of drop clusters—"puddles"—or an EHL layer, rather than by destruction of the individual drops and formation of a plasma.[1)] A layer is formed if the average density N_c of the liquid phase brought to the surface exceeds the value $n_0^{2/3} \approx 3.5 \times 10^{11}$ cm^{-2} ($n_0 = 2 \times 10^{17}$ cm^{-3} is the density of pairs in the EHL). In the steady-state case[8] $N_c = \overline{n} v \tau_s$, and the formation of an EHL layer at the surface for $\tau_s = 5 \times 10^{-7}$ sec and $v = 10^4$ cm/sec is possible, beginning with $\overline{n} > 7 \times 10^{13}$ cm^{-3}.

The absorption by an EHL layer at $P \approx 2P^{**}$ was normally ~10 times greater than that caused by Auger electrons under cyclotron-resonance conditions. Since Auger electrons with a density of ~10^{11} cm^{-3} (for $\overline{n} \approx 10^{14}$ cm^{-3}) fill the entire excited volume (~10^{-3} cm^3), we can estimate, in the manner of Eq. (1), the volume of the EHL layer which gives the observed absorption signal. Such an estimate gives ~10^{-7} cm^3, which corresponds to a 10^{-4}-cm-thick cluster with a diameter of ~300 μm. A similar estimate of this EHL layer can be determined from the expression for N_c; this confirms the validity of the interpretation of the observed microwave absorption.

In conclusion, we note that we produced the EHL layer by means of an external phonon stream that set the drops in motion. The earlier observed "anomalies" in absorption at high pumping levels[1,4] (Fig. 1e) are caused by the formation of an EHL layer. The threshold of EHD dispersion due to the action of intrinsic phonon wind is reached at $\overline{n} > 10^{15}$ cm^{-3}; in this case the drop velocity exceeds 10^3 cm/sec, and the conditions for layer formation are fulfilled with drop dispersion.

The small value of τ_c in the surface EHL accounts for the weak influence of the magnetic field on the absorbed power and produces a broad magnetoplasma resonance line in the EHL layer.[4]

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[1)] In principle, the absorption signal can be attributed to the appearance of a dense plasma near the surface, for example, by the bursting of drops in the field of the surface bending of the bands because of the loss of thermodynamic or kinetic stability of the surface layer of drops.

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