Microwave breakdown in Ge in a constant magnetic field

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A strong effect of the constant magnetic field on the pulsed uhf exciton breakdown in Ge in the presence of electron-hole drops at T = 1.3 K was observed. The dependence of the threshold breakdown strength on the magnetic field is compared with the cyclotron resonance spectrum. The collision frequency and temperature of the hot carriers is determined.

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Research at the P.N. Lebedev Institute[1] on the pulsed uhf breakdown of exciton gas in the presence of electron-hole drops (EHD) made it possible to determine a number of important characteristics of the system: free carriers-excitons-EHD, such as the concentration of the carriers in the drops, radius of the drops, and their lifetime.

Manenkov *et al.*[2] noticed that the external constant uhf field has an effect on the exciton breakdown in the constant microwave field. However, they did not conduct a detailed investigation or analyze the indicated effect.

In a pulsed uhf field the external magnetic field is also expected to greatly affect the exciton breakdown. In particular, the breakdown threshold should change, especially near the cyclotron resonance lines, and the time characteristics of the breakdown due to the capture of free carriers by the drops should also change. Investigation of the indicated effects can give new information on the dynamics of hot carriers and EHD and the collision frequency of the free carriers in strong uhf fields can be determined from the dependence of the breakdown threshold on the magnetic field strength.

In view of this, we investigated the pulsed uhf breakdown of exciton gas in Ge at $T = 1.3$ K in a constant magnetic field; we descovered that the magnetic field had a strong effect on the breakdown whose characteristics were studied.

The experimental setup was described in detail elsewhere.[1] The investigated sample was placed in the peak electric component of the uhf field E_0 in a rectangular cavity. The carriers were excited by YAG radiation: Nd^{3+} laser ($\lambda = 1.06$ μm, pulse duration 30 nsec, repetition frequency 12.5 Hz, pulse energy $\sim 10^{-4}$ J). The constant

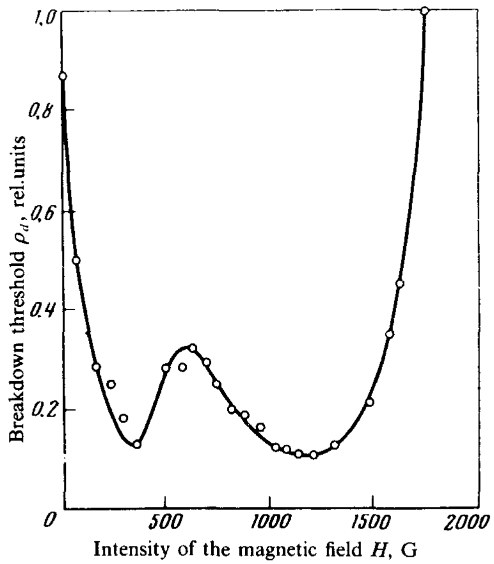

FIG. 1. Dependence of the Pd-threshold strength of the pulsed shf exciton breakdown in Ge at $T = 1.3$ K in the presence of EHD on the constant magnetic field H.

magnetic field was produced by an electromagnet, which could be rotated in the horizontal plane to change the orientation relative to the crystallographic axes of the Ge sample and the uhf field of the cavity.

The measurement of the pulsed breakdown threshold confirmed that it strongly depends on the magnetic field strength H. Figure 1 shows this dependence for the time lag of the uhf breakdown pulse relative to the exciting laser pulse of $\approx 150\,\mu$sec, which corresponds to the minimum threshold.[1] It is worth noting that position in time of the minimum of the threshold does not depend on H. It can be seen that the $P_d(H)$ curve has two minima at $\sim$400 and 1200-G fields, which are attributable to the cyclotron-resonance (CR) lines. In fact, the measurements of the CR spectrum at a much lower uhf power level than the exciton breakdown threshold showed (Fig. 2a) that there are two intensive CR lines in these magnetic fields. Thus, we conclude that the minima on the $P_d(H)$ curve are due to the cyclotron resonance and hence the collision frequency of the hot carriers can be estimated from the shape of the curve.

In general, to correctly determine the theoretical dependence of $P_d(H)$ we must solve the kinetic equation for the impact ionization in a constant magnetic field; however, for a qualitative explanation we can examine the model for the average electron.

The average power absorbed by a single carrier in the uhf field under CR conditions is given by

$$P_{\text{abs}}(H) = \frac{E_0^2\, e^2}{m\bar{\epsilon}^2 a^2}\,\frac{\nu}{\nu^2 + (\omega - \omega_c)^2} = P\,k\,(H), \tag{1}$$

where e, m, and ν are the charge, effective mass, and the collision frequency of the carriers, $\bar{\epsilon} = \epsilon_0 - 1 + 1/\alpha$, $\epsilon_0 = 16$ is the dielectric constant of the Ge lattice, α is the

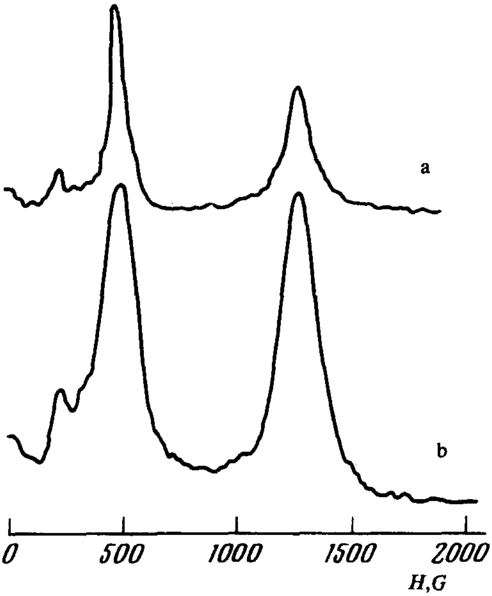

FIG. 2. Cyclotron resonance spectra of the free carriers in Ge in the presence of EHD: a, at low level of shf power ($\sim 10\ \mu$W); b, at increased power level (~ 2 mW). The orientation of the sample was slightly changed compared to that in Fig. 1.

depolarization coefficient of the sample in the electric field, ω is the uhf oscillator frequency, $\omega_c = eH/mc$ is the cyclotron frequency, P is the microwave input power, and $k(H)$ is the absorption coefficient.

Let us compare the experimental conditions under which the CR spectrum (Fig. 2) and the $P_d(H)$ curve (Fig. 1) were obtained. In the first case the input is constant $P=$ const, therefore $P_{\text{abs}}(H) \sim k(H)$-Cr spectrum. In the second case the average energy of the hot carrier ξ_{av} in the uhf field, which [at $\xi_{\text{av}} \sim kT$ (Ref. 2)] is proportional to $P_{\text{abs}}(H)$, corresponds to the ionization potential of the exciton at each point on the $P_d(H)$ curve. Thus, the experiment can be carried out at $P_{\text{abs}} =$ const; hence, $P = P_d(H) \equiv \text{const}/k_1(H)$. Here $k_1(H)$ is the absorption coefficient of the hot carriers.

Using Eq. (1) we determine from the $P_d(H)$ curve the collision frequency of the hot carriers 1.6×10^{10} sec^{-1}.

This value is much higher than the collision frequency of the cold carriers, which was measured at a low uhf power level ($\nu = 3 \times 10^9$ sec^{-1}) according to the width of the CR line.

The effect of the increase in the collision frequency was observed directly from the CR line broadening as a result of increasing the microwave power level (Fig. 2b).

It is known that at low temperatures the CR line broadening is due to the electron-phonon interactions for which the collision frequency depends on the energy of the carriers $\nu \sim \sqrt{\xi_{\text{av}}}$.[3]

Using the measured values for the cold and hot carriers, we can see that the energy of the carrier at the breakdown threshold under the conditions indicated above is $\xi_{\text{av}} = 37$ K, which is close to the binding energy of the exciton.

In the experiments we also noticed that the external constant magnetic field has a strong effect on the shape of the breakdown spike, which characterizes the development process of the cumulative ionization of excitons and the capture of the carriers by the drops.[1] This effect consisted in noticeable lengthening of the leading and trailing edges of the peak conductivity signal of the sample under breakdown conditions. Apparently this effect is attributable to the decrease in the cumulative ionization rate and capture of the carriers by EHD because of cyclotron twisting of the trajectories of the free carriers in the magnetic field.

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[3] P.S. Kireev, Fizika poluprovodnikov (Physics of Semiconductors), Vysshaya shkola, M., 1975, p. 402.