Observation and determination of the parameters of large electron-hole drops in germanium by means of microwave conductivity

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We investigated the microwave conductivity of inhomogeneously deformed Ge excited by laser pulses at a wavelength $\lambda = 1.06$ μ at helium temperatures. The existence of large electron-hole drops with radius up to 1 mm and density $\approx 2.5 \times 10^{16}$ cm^{-3}, particle binding energy $E_0 \approx 4.6$ meV, and lifetime $\tau_0 \approx 500$ μsec was observed.

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We report here observation and determination of the parameters of large electron hole drops (EHD) in Ge under conditions of inhomogeneous compression. Large electron hole drops were first observed in[1,2] by means of the Alfven size-effect resonance. Investigation of large drops was subsequently undertaken with the aid of luminescence[3,4] and IR sounding.[5] These studies were preceded by detailed investigations of the influence of uniaxial pressure on the spectrum of the recombination radiation of excitons and electron hole drops,[6–10] in which a decrease of the binding energy of the particles in the condensed phase, and motion of the electron hole drops were observed under the conditions of inhomogeneous deformation. Theoretical estimates of the parameters of the electron hole drops under inhomogeneous compression were obtained in[11,12].

We have attempted in this study to determine experimentally the main parameters of electron hole drops, using a microwave-conductivity and microwave-breakdown procedure employed by us earlier to investigate ordinary small electron-hole drops.[13] The experiments were performed on samples of pure dislocation-free germanium (residual impurity concentration 2.6×10^{11} cm^{-3}) in the form of a disk of 4 mm diameter and 2 mm thickness.

For inhomogeneous compression of the sample we used a construction similar to that described in[1,2]. The applied pressure was determined from the shift of the maximum of the EHD radiation and amounted to 950 kg/cm^2 in accordance with the data of[8]. We investigated the microwave conductivity of Ge at a frequency 10 GHz under pulsed laser excitation at a wavelength 1.06 μ (giant pulses of YAG:Nd^{3+} laser of duration 200 nsec with pulse energy 10^{-4} J) in the temperature region 4.2—1.3 °K.

Figure 1(a) shows a typical signal of the kinetics of microwave conductivity at $T = 4.2$ °K in the deformed sample. The signal is due to the free carriers, since it corresponds to a negative change of the real part of the complex dielectric constant ϵ' of the sample. It is natural to assume that this form of the microwave-conductivity signal is connected with the existence of large-size electron-hole drops having a long lifetime, and reflects the kinetics of the free

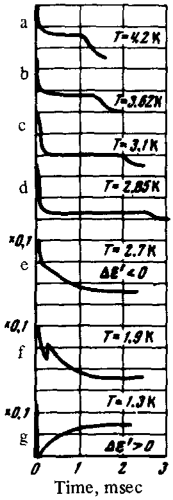

FIG. 1. Microwave-conductivity kinetics of deformed Ge at different temperatures and at a fixed excitation level corresponding to generation of ~ 10^{13} electron-hole pairs in the sample. In Figs. e, f, and g the initial section of the signal is bounded.

carriers evaporated by the drop. We note that in undeformed Ge, as shown earlier,[13] the corresponding times are smaller by two orders of magnitude. It appears that an essential role is played here by the presence of a pressure gradient, which hinders the diffusion of the excitons and carriers from the region of maximum pressure.

Our investigations of the kinetics of the microwave conductivity at different temperatures have shown that the amplitude of the section of the signal corresponding to the quasistationary carrier density decreases abruptly with decreasing temperature (Fig. 1(a)—1(d), Fig. 2), and tends to zero at $T \approx 2.8$ °K. This fact can be easily explained by assuming that the amplitude of the signal is proportional to the number n_e of the free carriers that are at equilibrium with the drop, for which

$$n_e \sim (kT)^{3/2} \exp\left(-\frac{E_0}{2kT}\right)^{1)}, \qquad (1)$$

where E_0 is the binding energy of the particles in the electron hole drop.

From a comparison of the plot of $\mathrm{In}[A/(T/T_0)^{3/2}$ against (I/T) (Fig. 2) with formula (1) we easily obtain the binding energy of the particles in a large electron-hole drop, namely $E_0 = 4.6 \pm 0.2$ meV.

In addition, when the temperature is lowered from 4.2 to 2.85°K, a lengthening of the quasistationary section of the signal is observed at a fixed excitation level. This result is obviously connected with an increase of the lifetime of the large electron-hole drop, due to the decrease of the evaporation at lower temperatures. It has been noted in[2], however, that evaporation from a large drop at $T = 4.2$ °K is strongly suppressed. Our data show that this process becomes negligibly small only at temperature $T \leq 2.8$ °K, when the main source of the free carriers is the burst due to the Auger process. In the temperature range 2.8—2 °K, the signal becomes exponential with a time constant 750 μsec (Fig. 1(e)). In this case the microwave conductivity is due to Auger electrons.[14] With further decrease of the temperature, the microwave conductivity signal becomes strongly deformed: at $T = 13$ °K (Fig. 1(g)) the exponential reverses

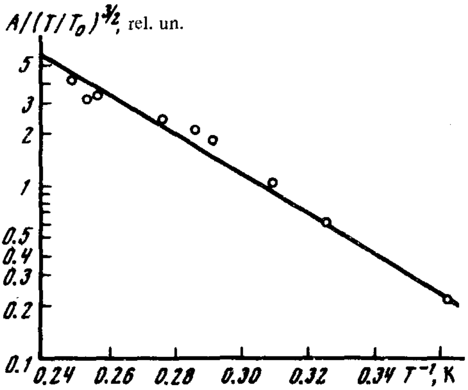

FIG. 2. Dependence of the amplitude of the quasistationary section of the signal on the temperature. The slope of the plot of $\ln[A/(T/T_0)^{3/2}$ against $1/T$ makes it possible to obtain the binding energy of the particles in a large electron hole drop, $E_0 = 4.6$ meV.

polarity and has a time constant ≈ 500 μsec. The main contribution to the microwave conductivity is made then not by the free carriers (their density is low) but by the drop itself. This is easily understood, since a large drop crowds out the microwave field, causing in fact detuning of the resonator. The kinetics of this signal describes the decay of the drop and makes it possible to determine directly its lifetime, $\tau_0 = 500$ μsec.

Measurement of the detuning due to the crowding out of the field from the drop yielded a value ~ 1.5 MHz at the maximum excitation level, and this made it possible to estimate the dimension of the electron hole drop at $R \approx 1$ mm. Hence, knowing the energy of the exciting pulse, it is easy to obtain the particle density in the drop. We obtain $n_0 = 2.5 \times 10^{16}$ cm^{-3}, in agreement with theoretical estimates.[11,12]

Investigations of microwave breakdown of an exciton gas have shown that in presence of a large drop a "hot" breakdown of excitons takes place, lasting the entire time of the microwave pulse. The lifetime of the breakdown after the laser pulse coincides with the duration of the quasistationary section of the microwave conductivity signal and amounts to several milliseconds, depending on the excitation level. The breakdown threshold increases monotonically with increasing delay time. The characteristic features of the microwave breakdown of an exciton gas, in the presence of a large drop, differ radically from the case of microwave breakdown in undeformed germanium, which was investigated in detail in[13]. The absence of a sharp breakdown spike and of a minimum breakdown threshold indicate that one large drop, owing to the abrupt decrease of its surface (by an approximate factor of 100 in comparison with a cloud of small drops) exerts no influence on the development of the electron avalanche, and the breakdown of the excitons takes place as in an ordinary gas.

Thus, our investigations confirm the existence, in deformed germanium, of one large electron-hole drop of radius 1 mm with particle density $n \approx 2.5 \times 10^{16}$ cm^{-3}, binding energy $E_0 \approx 4.6$ meV, and lifetime $\tau_0 \approx 500$ μsec.

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[1] This formula does not take into account the change of the effective volume of the drop due to the presence of the deformation potential well.

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