Dependence of the density of electron-hole drops on their size in inhomogeneously deformed germanium

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A comparison of the results of measurements of the pulsed microwave conductivity and recombination radiation of electron-hole drops (EHD) in inhomogeneously deformed Ge shows that the average carrier concentration in the EHD increases with increasing drop size.

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In recent years, great interest has arisen in the study of large electron-hole drops (EHD) which are formed during optical pumping of inhomogeneously deformed Ge.[1] The size of such EHD may reach 1 mm, the lifetime ~500 μsec, and the density is $\sim 2.5 \times 10^{16}$ cm^{-3}.[2] The inhomogeneity of the concentration of particles within large EHD was predicted in Ref. 3. Assuming that the deformation energy in the potential well has a parabolic dependence and the chemical potential is constant in the entire drop, Markiewicz and Kelso[3] obtained an expression for the dependence of the carrier concentration on the radius (r) of the drop:

$$n(r) = n_0 [1 + \hat{a}(R^2 - r^2)], \tag{1}$$

where $\hat{a} = a/n_0^2 E_0''$, $E_0'' = (d^2E/dn^2)_{n=n_0}$, E_0 and n_0 are the equilibrium energy of a pair of particles and the density of the EHD at a given pressure, α (MeV/mm^2) is a pressure-dependent coefficient, and R is the initial radius of the drop.

It follows from Eq. (1) that the particle concentration at the center of the drop is larger than the equilibrium concentration at a given pressure. In this model it is assumed that the entire drop is located at the potential energy minimum and that additional compression at the center of the drop is due to the pressure gradient in the potential well. In Ref. 4 the distribution of the particle density in the EHD as a function of the radius was studied experimentally by measuring the spatial profile of the luminescence intensity during continuous optical pumping. These measurements confirmed the validity of Eq. (1).

These investigations were not performed under conditions of pulsed excitation of carriers and observation of the EHD kinetics; moreover, they are of great interest in determining whether the aforementioned model for compression of the EHD in a nonuniform deformation field is adequate. In this paper we performed such investigation using a method based on simultaneous measurement of the kinetics of microwave conductivity and recombination radiation of Ge as a result of a pulsed laser excitation. The method of measuring the average concentration of the particles in EHD in these experiments is as follows. For large EHD the signal (P_{micro}) observed by means of a microwave spectrometer at $T \approx 1$K is due primarily to detuning of the microwave cavity ($\Delta\omega$) that contains the test sample, and this detuning is proportional to the

EHD volume (v_{EHD}):

$$\Delta\omega \sim \frac{v_{\mathrm{EDH}}}{v_p}\,\omega_0{}^{1)} \; .$$

The intensity of the EHD recombination radiation (L) is proportional to the total number of particles in it. Therefore, by measuring in the same experiment the kinetics of the microwave-conductivity signals and the luminescence, we can determine the particle density in the EHD $\bar{n} = \beta^{L}/P_{\mathrm{micro}}$ (β is a coefficient) and its time evolution.

The experiments were carried out at $T = 1.3$ K, using samples of dislocation-free, n-type Ge with a residual impurity concentration of $\sim 7\times10^{11}$ cm^{-3} in the shape of a 4-mm-diam and 2-mm-thick disk, which was compressed nonuniformly in the $\langle 111\rangle$ direction. Optical excitation was accomplished by a pulsed YAG:Nd^{3+} laser ($\lambda = 1.06$ μm). The setup for simultaneous recording of the microwave conductivity and luminescence is similar to that described in Ref. 5. The device for compressing the sample was described in Ref. 2. All the results given below are for an applied pressure of $P \approx 1500$ kg/cm^2, which was determined from the shift of the maximum of the EHD emission line according to the data of Ref. 6. The size of the EHD was varied by laser excitation of the sample.

The kinetics of the microwave conductivity and luminescence and the EHD emission spectra were recorded for different levels of optical excitation of the Ge sample.

Figure 1 shows the dependence of the signal amplitude of the microwave conductivity and luminescence of EHD on the intensity of laser pumping. It can be seen that, in contrast to the luminescence signal for which the amplitude L is proportional to the pumping intensity I, the microwave-conductivity signal in the range $I < 0.15\ I_0$ varies nonlinearly with I. We can assume that this is due to the variation of the average

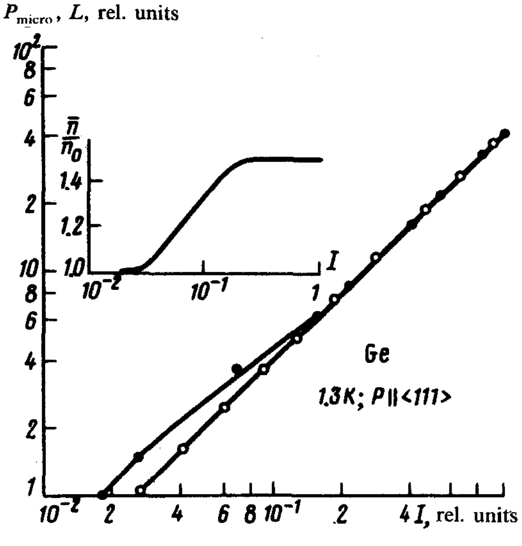

FIG. 1. Dependence of the signal amplitude of the microwave conductivity P_{micro} (●) and luminescence L (○) of inhomogeneously deformed Ge in the $\langle 111\rangle$ direction; on the intensity of the optical excitation. $T = 1.3$ K and $P = 1500$ kg/cm^2. For $I = 1$ $\sim 4\times10^{13}$ electron-hole pairs are excited in the sample, $R \approx 0.6$ mm (if we assume that $\bar{n} = 5\times10^{16}$ cm^{-3}). The inset shows the dependence of the average EHD density $\bar{n}/n_0$ on pumping taken from the data in Fig. 1.

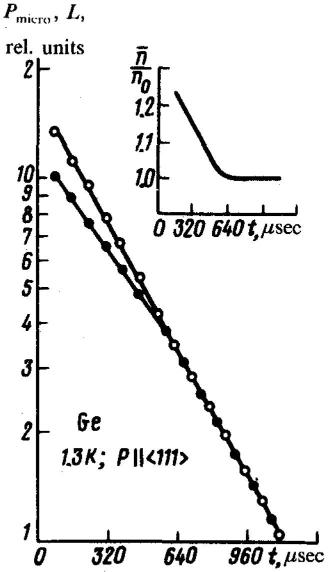

FIG. 2. Kinetics of the microwave conductivity $P_{\text{micro}}(t)$ (●) and luminescence $L(t)$ (○) of inhomogeneously deformed Ge in the $\langle 111\rangle$ direction. $T = 1.3$ K and $P = 1500$ kg/cm^2. The initial radius of the EHD is ~ 0.3 mm. The time constants for the curves are: $\tau_r \approx 510$ μsec ($t < 600$ μsec), $\tau_r \approx 400$ μsec ($t > 600$ μsec), and $\tau_L \approx 400$ μsec. The inset shows the time dependence of $\bar{n}/n_0$ taken from the data in Fig. 2.

concentration of particles density in the EHD. The function $\bar{n}/n_0(I) = \beta \dfrac{L(I)}{P_{\text{micro}}(I)}$ in the inset of Fig. 1 indicates that the average density of the EHD increases by a factor of 1.5 when the excitation level of the electron-hole pairs increases in the sample from $\sim 8\times 10^{11}$ to 6×10^{12}.

To determine the variation of the average density of the drop during its recombination, we measured the time characteristics of the recombination radiation and the microwave conductivity. Figure 2 shows the curves for attenuation of the luminescence $L(t)$ and microwave conductivity $P_{\text{micro}}(t)$ after the laser pulse. For delay times $t < 600$ μsec $\tau_r > \tau_L$, and the time constants for both curves are equal. Assuming, as before, that $\bar{n}/n_0(t) = \beta L(t)/P_{\text{micro}}(t)$, we noticed that the average particle concentration in the drop decreases by $\sim 25\%$ as a result of its recombination (inset in Fig. 2).

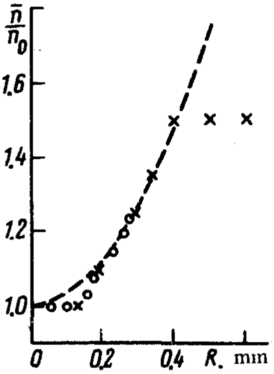

FIG. 3. Dependences of $\bar{n}/n_0$ on the EHD radius, obtained from the data in Fig. 1 (x) and Fig. 2 (●). The dashed line represents the dependence $\bar{n} = n_0(1 + \frac{2}{5}\hat{\alpha}R^2)$ for $\hat{\alpha} = 7$ mm^{-2}.[3]

Apparently, the variation of $\bar{n}$ in the EHD, which is a function of excitation of time, is attributable to the variation of the size of the drop. This is confirmed by the data in Fig. 3, where the dependences $\bar{n}/n_0(I)$ and $\bar{n}/n_0(t)$ are plotted as functions of the EHD radius for which, as noted above, $R^3 \sim P_{micro}$. It can be seen that both dependences are in good agreement with each other. A comparison with the theoretical curve $\bar{n}(R) = n_0 (1 + \frac{2}{5} \hat{\alpha} R^2)$, which follows from Eq. (1) after averaging $n(r)$ over the volume of the drop, gives a qualitative agreement with the experiment in the region of small radii of the drop. For large radii, however, the density does not change. We can assume that under these conditions the quadratic approximation for the shape of the potential well is inapplicable.

In conclusion, the authors thank L.V. Keldysh for a discussion of the results.

(1) The validity of the relation $v_{\text{EHD}}/v_r \sim \Delta\omega/\omega_0$, where v_r is the cavity volume and ω_0 is its natural frequency, was verified by a direct simulation of the EHD by a metallic particle.[2]

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