

## HEATING OF ELECTRON-HOLE DROPS IN AN INHOMOGENEOUS-DEFORMATION FIELD

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It is shown that electron-hole drops become heated in non-uniformly deformed germanium. This accelerates the evaporation of the carriers from the drops and leads to a characteristic increase of the conductivity of the crystals.

It was shown in [1] that electron-hole drops in germanium can move over macroscopic distances in a non-uniform deformation field, from the excitation region into the region of maximum deformation. This was seen to be accompanied by an extremely sharp reduction, by several orders of magnitude, in the intensity of the recombination radiation of the condensed phase. We propose that such a decrease in the radiation intensity can be due to heating of the moving-drop plasma by interaction with phonons [2]. This heating should increase the rate of evaporation of the electrons and holes from the drop and increase the conductivity of the crystal. We emphasize that the evaporation rate is determined just by the drop temperature  $T_e$  and not by the crystal-lattice temperature  $T$ .

For a qualitative description of the change of the crystal conductivity, we assume the deformation gradient to be constant and the time within the drop motion sets in to be sufficiently short. The drop temperature  $T_e$  can then be assumed to be constant in time and in space, but dependent on the deformation gradient. We assume furthermore that the crystal is excited by a light pulse, and by the time the pulse terminates almost all the carriers are bound into electron-hole drops, so that further capture of the free excitons by the drops can be neglected. After the termination of the excitation, the change in the number of carriers in a drop of radius  $R$  is then described by the equation [3]

$$\frac{d}{dt} \left( \frac{4}{3} \pi R^3 n_0 \right) = - \frac{4}{3} \pi R^3 \frac{n_0}{\tau_0} - 4 \pi R^2 A T_e^2 \exp \left( - \frac{\phi}{k T_e} \right). \quad (1)$$

Here  $n_0$  is the carrier concentration in the condensed phase,  $\tau_0$  is the lifetime of the condensed phase,  $A$  is the Richardson constant, and  $\phi$  is the work function. It follows from (1) that

$$R = \left[ R_0 + \frac{3 \tau_0 A T_e^2}{n_0} \exp \left( - \frac{\phi}{k T_e} \right) \right] \exp \left( - \frac{t}{3 \tau_0} \right) - \frac{3 \tau_0 A T_e^2}{n_0} \exp \left( - \frac{\phi}{k T_e} \right), \quad (2)$$

where  $R_0$  is the initial radius of the drop. We see that  $R$  decreases to zero within a time  $t_c$ :

$$t_c = 3 \tau_0 \ln \left[ 1 + \frac{R_0 n_0}{3 \tau_0 A T_e^2} \exp \left( \frac{\phi}{k T_e} \right) \right]. \quad (3)$$

If  $t_c < 3 \tau_0$ , then

$$t_c = \frac{R_0 n_0}{A T_e^2} \exp \left( \frac{\phi}{k T_e} \right) \quad (4)$$

and

$$R = R_0 (1 - t/t_c). \quad (5)$$

Assuming that the concentration  $n$  of the free electrons and holes, which determines the conduc-

tivity of the crystal, is changed only as a result of the carrier evaporation from the drops and their binding into excitons, we can put  $\alpha n^2 = (4\pi N n_0 R_0^3 / t_c)(1 - t/t_c)^2$ , whence

$$n = \left( \frac{4\pi N n_0 R_0^3}{\alpha t_c} \right)^{1/2} (1 - t/t_c). \quad (6)$$

Here  $N$  is the drop concentration and  $\alpha$  is the coefficient of binding of the electrons and holes into excitons. Thus, the crystal conductivity should decrease linearly with time, dropping to zero within a time  $t_c$  that is connected with the temperature  $T_e$  of the electron-hole plasma of the drops by Eq. (4). We note that an investigation of the dependence of  $t_c$  on the lattice temperature  $T$  was used in [4] to determine the work function  $\phi$  from electron-hole drops in germanium.

In the experimental study of the drop heating, a pure germanium sample was excited by radiation pulses from a GaAs laser, of energy  $10^{-6} - 10^{-7}$  J and duration  $2 \times 10^{-7}$  sec. The sample was 2 mm long and was cut in the [111] direction. The deformation gradient, proportional to the pressure gradient  $\partial p / \partial x$  was produced by a force directed along the sample, the cross section of which varied from 2.25 mm<sup>2</sup> on the ends to 1.5 mm<sup>2</sup> in the central part. To measure the conductivity, indium contacts were deposited on the lateral surfaces of the sample. Oscillograms were taken of the current through the sample, which was proportional to the sample conductivity. The electric field intensity in the sample did not exceed 0.3 V/cm.

Figure 1 shows oscillograms of the current  $i$  through the sample at two temperatures and at different pressure gradients. It is seen from the figure that the time dependence of the conductivity agrees with expression (5), and the time  $t_c$  at which the conductivity vanishes decreases with increasing sample temperature  $T$  or with increasing pressure gradient. The decrease of  $t_c$  with increasing pressure was accompanied by a decrease of more than two orders of magnitude in the integral intensity of the recombination radiation. A typical plot of the cutoff time  $t_c$  against the pressure gradient  $\partial p / \partial x$  is shown in Fig. 2. This figure shows also the

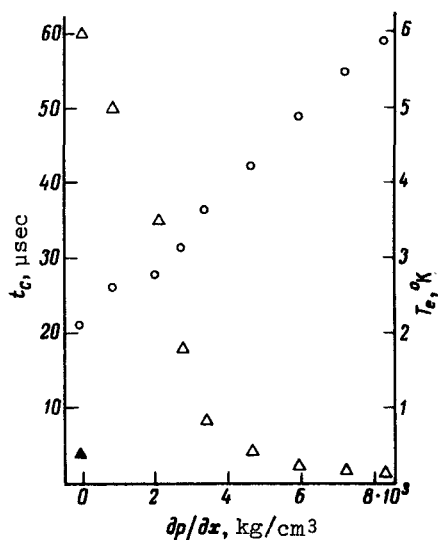


Fig. 1

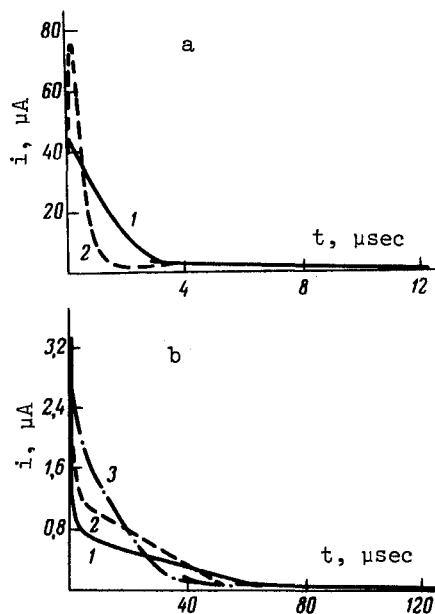


Fig. 2

Fig. 1. Time dependence of the current  $i$  through the sample at different temperatures  $T$  and pressure gradients  $\partial p / \partial x$ : a - 1)  $T = 4.2^\circ\text{K}$ ,  $\partial p / \partial x = 0$ ; 2)  $T = 2.1^\circ\text{K}$ ,  $\partial p / \partial x = 7200 \text{ kgf/cm}^3$ . b -  $T = 2.1^\circ\text{K}$ : 1)  $\partial p / \partial x = 0$ ; 2)  $\partial p / \partial x = 870 \text{ kgf/cm}^3$ ; 3)  $\partial p / \partial x = 2100 \text{ kgf/cm}^3$ .

Fig. 2. Cutoff time  $t_c$  ( $\Delta$ ) and drop temperature  $T_e$  (o) vs the pressure gradient  $\partial p / \partial x$  at  $2.1^\circ\text{K}$ ;  $\blacktriangle$  -  $t_c$  at  $T = 4.2^\circ\text{K}$  and  $\partial p / \partial x = 0$ .

drop temperature  $T_e$  calculated from (4), using the values  $\phi = 1.5$  meV [4, 5] and  $t_c = 3.5$  usec at 4.2°K (Fig. 1a). It is seen from Fig. 2 that the drop temperature  $T_e$  increases approximately in proportion to the pressure gradient and reaches ~6°K. Naturally, at such a high temperature the electron-hole drops in the germanium evaporate almost completely and there is no more recombination radiation from the condensed phase of non-equilibrium carriers.

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#### EPR OF FREE RADICAL DPPH AT INFRALOW TEMPERATURES

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The study of the magnetic properties of organic paramagnets of the free-radical type at very low temperatures is of undisputed interest, since simple magnetic-system models that lend themselves to a rigorous theoretical analysis, are frequently realized in such paramagnets. One of the most thoroughly studied representatives of this class of substances is the free radical  $\alpha$ -diphenyl- $\beta$ -picrylhydrazyl (DPPH).

Vanishing of the resonance signal at temperatures  $T_{cr} = 0.2 - 0.3^\circ\text{K}$  in DPPH samples crystallized from benzene was first observed at low frequencies in [1] by the EPR method. This fact was interpreted as the result of a phase transition into an antiferromagnetic state, and the absence of such a transition at high frequencies [2] was attributed in [1] to destruction of the antiferromagnetic order by the constant magnetic field necessary to satisfy the resonance conditions.

We report here observation of a phase transition in two types of DPPH samples at temperatures below 1°K, using an EPR method at intermediate frequencies (300 MHz). The specimens were finely crystallized powders of the radical, crystallized from two solvents, benzene and chloroform.

The EPR signal was detected with a superheterodyne spectrometer at a working power level on the order of  $10^{-7}$  W to exclude spin saturation and high-frequency heating of the sample. Temperatures below 1°K were produced by adiabatic demagnetization of a block of paramagnetic iron ammonium alum salt, with which the sample was in contact through a copper cold finger. Demagnetizing fields on the order of 20 kG were obtained with a small superconducting solenoid.

The results are listed in the table:

Sample type	$t_m$ , °C	$\delta H(4.2^\circ\text{K})$ , G	$\delta H(1.8^\circ\text{K})$ , G	$T_{cr}$ , °K
DPPH(I) (from benzene)	106	5.3	5.9	$0.25 \pm 0.15$
DPPH(II) (from chloroform)	120	3.1	3.8	$0.9 \pm 0.1$

where  $t_m$  is the melting temperature of the sample,  $\delta H$  is the peak EPR line width at the corresponding temperature, and  $T_{cr}$  is the temperature at which the EPR signal vanishes.

The value of  $T_{cr}$  obtained for the benzene sample agrees well with the results of [1], in spite of the fact that our measurements were made at large values of the constant magnetic field. This means that in measurements up to 300 MHz the exchange energy still exceeds the Zeeman energy appreciably.