Nonequilibrium orientation of electrons in electron-hole drops in silicon in a magnetic field

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We investigated the circular polarization of recombination radiation of electron-hole drops in silicon in a magnetic field up to 50 kOe at a temperature 1.9°K. We have observed that the electrons oriented in a magnetic field in free excitons retain their orientation, after the excitons become bound into EHD, during the lifetime of the drops.

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In our preceding paper[1] we have observed a large polarization of the radiation of electron-hole drops (EHD) in silicon in a magnetic field. Further investigations have shown that the observed polarization is due to the nonequilibrium orientation of the electrons in the EHD as a result of preservation of the orientation that is produced prior to condensation, when the electrons are located in the free excitons (FE).

The experiments were performed on films of pure silicon 250 μ thick. The excited surface of the silicon was treated with a polishing etchant, and the opposite surface was carefully polished mechanically. The circular polarization was measured in a Faraday geometry with the aid of a rotating quarter-wave plate and a stationary polaroid.[2] The radiation was excited with an argon laser.

Figure 1 shows a plot of the degree of circular polarization of the radiation of

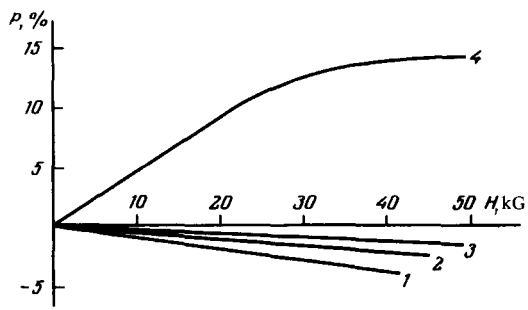

FIG. 1. Dependence of the degree P of circular polarization of the radiation on the magnetic field $H \parallel [111]$ at a temperature $T = 1.9$ °K in pure silicon ($\rho \sim 6500$ Ω-cm): 1,2,3—EHD, $h\nu = 1.087$ eV, TO phonon; excitation level increases from 1 to 3; 4—free exciton, $h\nu = 1.098$ eV, TO phonon; 3 and 4 correspond to the same excitation level. The noise level of the apparatus corresponds to 0.5% polarization.

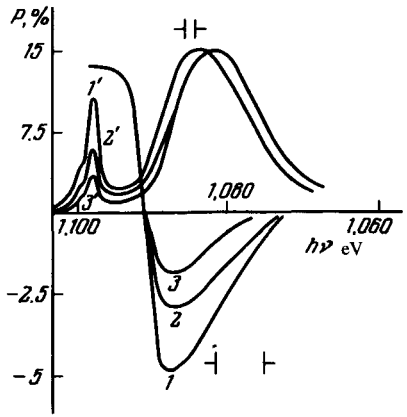

FIG. 2. Spectral distribution of the radiation ($1', 2', 3'$) and of the polarization $P(1,2,3)$ in a field $H = 48$ kOe at a temperature $T = 1.9$ °K in pure silicon ($\rho \sim 6500\ \Omega - \text{cm}$): 1, 2, and 3 correspond to $1'$, $2'$, and $3'$.

the free excitons and the EHD vs. the magnetic field H at different excitation levels. The corresponding spectral distribution of the polarization and of the radiation in a field $H = 48$ kOe is shown in Fig. 2. The emission spectra were normalized to the maximum of the EHD emission line. It is seen from Fig. 2 that the maximum of the spectral distribution of the polarization is located at the short-wave edge of the EHD emission line, and that the polarization increases with increasing intensity of the FE radiation. In doped samples containing 3×10^{15} cm^{-3} boron atoms, the EHD radiation turned out to be practically unpolarized. There was no FE emission line in these samples, because of their rapid binding of the excitons with the impurities, while the emission line of excitons bound with neutral acceptors (1.0933 eV) was strongly polarized.[1]

The anomalously large polarization of the EHD emission line, and the dependence of the degree of polarization on the relative intensity of the FE radiation show this to be a non-equilibrium polarization. This polarization is opposite in sign to the polarization of the Fe radiation and of the radiation of excitons bound with boron atoms, thus indicating that the electrons in the EHD are oriented. (The sign given in[1] for the EHD radiation is incorrect). It follows from the curves of Fig. 2 that at $H = 48$ kOe, for the lowest excitation level, the degree of orientation of the electrons is maximal and amounts to $P_d = (n^+ - n^-)/(n^+ + n^-) = 0.4$ (n^+ and n^- are the numbers of electrons oriented parallel and antiparallel to the field, respectively). The radiation depolarization factor, which is needed to determine the true value of the polarization, is determined, as in[1], from the degree of the exciton polarization, the magnitude and sign of which are connected with the hole orientation. A strong argument in favor of the assumption that the electrons in the EHD have a nonequilibrium orientation is the spectral distribution of the polarization, inasmuch as in the case of equilibrium orientation the polarization has a maximum at the long-wave edge of the line.

The dependence of the degree of polarization of the EHD radiation on the excitation level shows that under the experimental conditions the spin-relaxation time τ_s^e, of the electron in the exciton is comparable with the exciton lifetime τ_{ex}, which is determined by the rate of the binding of the FE into EHD. Therefore the degree P_{ex} of orientation of the electrons in the exciton does not reach the equilibrium value P_{ex}^0 and can be represented in the form

$$P_{ex} = \frac{P_{ex}^{\circ}}{1 + (1 + |P_{ex}^{\circ}|)\dfrac{\tau_s^{\circ}}{\tau_{ex}}}, \quad (1)$$

The time τ_{ex} can be determined from the ratio of the FE and EHD radiation line intensities J_{ex} and J_d, respectively:

$$\tau_{ex} = \tau_d \frac{J_{ex}}{J_d} \frac{\tau_{ex}^{\circ}}{\tau_d^{\circ}}, \quad (2)$$

where τ_{ex}^0 and τ_d^0 are the radiation times in the exciton and the EHD, respectively, and $\tau_d \approx 1.5 \times 10^{-7}$ sec[3] is the pair lifetime in the EHD and does not depend on the excitation level. With the aid of (2) we find that on going from curve 3 to curve 1 of Fig. 2 the value of τ_{ex} changes approximately from 10^{-7} to 10^{-8} sec.

Estimates show that the only known electron spin relaxation mechanism capable of ensuring a faster relaxation in the exciton (compared with the EHD) and leading to $\tau_s^e < 10^{-7}$ sec is exchange interaction of the electrons with the holes. According to[4], at $\Delta \tau_s^h / \hbar \ll 1$ this mechanism yields

$$\tau_s^e = \frac{8}{5} \frac{\hbar^2}{\Delta^2 \tau_s^h} [1 + (\omega \tau_s^h)^2]. \quad (3)$$

Here Δ is the exchange splitting in the exciton, τ_s^h is the time of the spin relaxation of the holes in the exciton, $\hbar\omega = (g_e - g_h)\mu_0 H$, g_e and g_h are the electron and hole g factors. In accordance with (1) and (3), at the indicated values of τ_{ex} and at $H \sim 50$ kOe, the degree of orientation of the electrons in the exciton can reach $P_{ex} > 0.5$ at $\Delta \gtrsim 10^{-5}$ eV.

The degree of nonequilibrium orientation of the electrons in EHD is given by

$$P_d = \frac{P_{ex}}{1 + \dfrac{\tau_d}{\tau_s^d}}, \quad (4)$$

where τ_s^d is the electron spin relaxation time in the EHD. The large experimental value of P_d demonstrates that τ_s^d in EHD exceeds $\tau_d \approx 1.5 \times 10^{-7}$ sec. At $\Delta \gtrsim 10^{-5}$ eV, the principal spin-relaxation mechanism of the electrons in EHD is the exchange interaction of the electrons with the holes, which yields according to[5]

$$\tau_s^d \approx 10^3 \frac{E_B^3 \hbar}{(E_F^e \Delta)^2} \approx 10^{-10} \left(\frac{E_B}{\Delta}\right)^2 \text{sec}. \quad (5)$$

Here E_B and E_F^e are the Bohr and Fermi energies of the electrons. It is seen from (4) and (5) that at $\tau_d \approx 1.5 \times 10^{-7}$ sec the electrons do not lose their orientation in the EHD if $\Delta < 10^{-4}$ eV. The range $\Delta \sim 10^{-4}$—10^{-5} eV agrees with the theoretical estimates of Δ in silicon.

It should be noted that the appreciable orientation of the electrons in the EHD should have led to an appreciable change in the position and shape of the emis-

sion band. We were unable, however, to observe changes in the shape and position of the line as functions of the magnetic field.

We note in this connection that an appreciable nonequilibrium orientation of electrons could take place also in a biexciton, if the total angular momentum of the holes in the ground state of the biexciton is $J=0$, and the electrons are in different valleys. Owing to the decrease of the effective exchange interaction of the electrons with the holes, which is determined under these conditions by the quantity $\Delta_{ef}=\Delta^2/\Delta_{20}$ (where Δ_{20} is the energy difference between the states with $J=2$ and $J=0$), the time of spin relaxation of the electrons in the biexcitons should increase appreciably. This model explains the spectral distribution of the polarization, or the experimentally observed displacement of the short-wave edge of the EHD line towards the exciton line with decreasing excitation level. This line shift (which is not connected with the presence of the magnetic field) can be attributed to the change of the binding energy in the EHD with decreasing drop radius.

In conclusion, we wish to call attention to the fact that the polarization of the radiation located between the exciton line and the EHD line in the spectrum of Fig. 2 has the same sign and is close in magnitude to the exciton polarization. This allows us to assume that this radiation does not belong to very small drops. In our opinion this radiation can be connected only with complexes containing free holes (exciton + electron) or with complexes with two holes and a total angular momentum $J=2$ (exciton + hole or biexciton). When the temperature is raised from 1.9 to 5 °K, the radiation decreases rapidly in this region of the spectrum.

[1]P. D. Altukhov, G. E. Pikus, and A. A. Rogachev, Pis'ma Zh. Eksp. Teor. Fiz. **23**, 635 (1976) [JETP Lett. **23**, 582 (1976)].
[2]V. M. Asnin, Yu. N. Lomasov, and A. A. Rogachev, Pis'ma Zh. Tekh. Fiz. **1**, 596 (1975) [Sov. Tech. Phys. Lett. **1**, 268 (1975)
[3]W. Schmid, Solid State Commun. **19**, 347 (1976).
[4]G. E. Pikus and G. L. Bir, Zh. Eksp. Teor. Fiz. **67**, 788 (1974) [Sov. Phys. JETP **40**, 390 (1975)].
[5]G. L. Bir, A. G. Aronov, and G. E. Pikus, Zh. Eksp. Teor. Fiz. **69**, 1382 (1975) [Sov. Phys. JETP **42**, 705 (1976)].