Circular polarization of recombination radiation of silicon in a magnetic field at a high excitation evel

P. D. Altukhov, G. E. Pikus, and A. A. Rogachev

A. F. Ioffe Physico-technical Institute, USSR Academy of Sciences

(Submitted April 27, 1976)
Pis'ma Zh. Eksp. Teor. Fiz. **23**, No. 11, 635–639 (5 June 1976)

We investigated the circular polarization of the emission line with maximum energy 1.082 eV and the emission lines of free and bound excitons in silicon in magnetic fields up to 50 kOe in the temperature interval 1.9–15°K. The polarization of the 1.082-eV line exceeds by more than one order of magnitude the value expected in the simple exciton-condensate model.

PACS numbers: 78.60.—b, 78.20.Ls

An investigation of the circular polarization of radiation in a magnetic field makes it possible to determine the magnitude and sign of the g-factors of the electrons and holes[1,2] and may turn out to be most useful in the case of emission lines whose spectral widths exceeds their Zeeman splittings.

We investigate in this paper the circular polarization of a broad emission ine with energy maximum 1.082 eV, produced in silicon at a high excitation evel,[3,4] and of the emission lines of free and bound excitons.

For free and bound excitons, the polarization of the emission in weak magnetic fields should increase linearly with increasing magnetic field and reach saturation at $g_1\mu_0H$, $g\mu_0H \gg kT$ (where H is the magnetic field, μ_0 is the Bohr magneton, g_1 and g are the g-factors of the holes and electrons, respectively, and kT is the temperature). In weak fields, the degree of circular polarization of the radiation is equal to

$$P_{\text{circ}}(H) = \Phi_N(\langle J_z\rangle - \langle S_z\rangle), \tag{1}$$

where $\langle J_z\rangle$ and $\langle S_z\rangle$ are the average angular momenta of the holes and electrons, respectively. The factor Φ_N depends on the ratio of the matrix elements that determine the probabilities of the transitions through various intermediate states, and can differ in magnitude and in sign for transitions with participation of LO, LA, TA, and TO phonons or a zero-phonon (NF) emission line. For the zero-phonon emission line of an exciton bound with a neutral donor in the state Γ_1 we have $\Phi_N = \Phi_{NF} = 1$.

In the case of an exciton bound with a neutral donor, the angular momenta of the electrons in the ground state of the exciton are antiparallel, the electrons are not oriented in the magnetic field, i.e., $\langle S_z\rangle = 0$, and the magnitude and sign of the polarization are determined by the magnitude and sign of the hole g-factor. Then

$$\langle J_z\rangle = -\frac{5}{4}\,\frac{g_1\mu_0 H}{kT}. \tag{2}$$

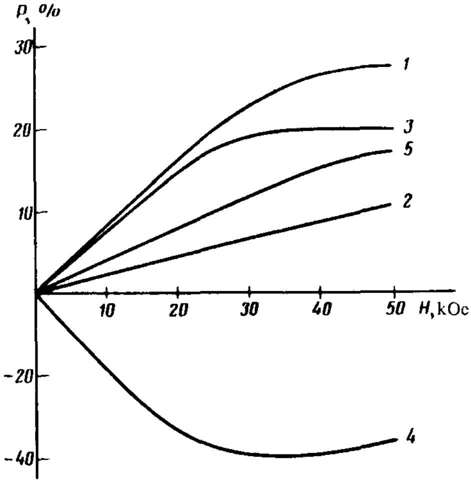

FIG. 1. Dependence of the degree of circular polarization P of the radiation on the magnetic field H at a temperature $T = 1.9\,^\circ\mathrm{K}$: 1, 2, 3, 4) n-Si : P with resistivity $\rho \sim 100\ \Omega$ cm; 5) p-Si : B, $\rho \sim 5\ \Omega$ cm. 1) Free exciton, $h\nu = 1.098$ eV, transition with TO-phonon emission; 2) line with $h\nu_{\max} = 1.082$ eV, $h\nu_{\max} = 1.082$ eV, TO phonon; 3, 4) exciton bound with neutral donor (phosphorus); 3) $h\nu = 1.0925$ eV, TO phonon; 4) $h\nu = 1.151$ eV, zero-phonon transition; 5) exciton bound with neutral acceptor (boron), $h\nu = 1.0933$ eV, TO phonon.

For an exciton bound with a neutral acceptor in a state with total hole angular momentum $I = 0$ we have $\langle J_z \rangle = 0$, while in the state with $I = 2$ we have

$$\langle J_z \rangle = -\frac{g_1 \mu_0 H}{kT}. \tag{3}$$

In both cases, $\langle S_z \rangle = -\frac{1}{4}(g\mu_0 H/kT)$. For a degenerate gas of non-interacting electrons and holes, according to[5],

$$\langle J_z \rangle = -\frac{15}{8}\,\frac{g_1 \mu_0 H}{E_F^h}, \quad \langle S_z \rangle = -\frac{3}{8}\,\frac{g \mu_0 H}{E_F^e}, \tag{4}$$

where E_F^h and E_F^e are the Fermi energies of the holes and electrons, respectively.

The circular polarization of silicon emission was measured in Faraday geometry at $H \parallel [111]$ with the aid of a procedure analogous to that used in[6]. The radiation was excited with an argon laser. Figure 1 shows the dependence of the degree of polarization P of the radiation on the magnetic field H for the emission lines of free excitons, and excitons bound with neutral donors (phosphorus) and neutral acceptors, and of the 1.082 eV line. Recognizing that the zero-phonon emission line of an exciton bound with a neutral donor has a theoretical saturation polarization $P_{\mathrm{circ}}^{\mathrm{sat}} = -1$, we can determine the radiation depolarization factor and the true polarizations of all the lines.

From the value of the polarization of the zero-phonon emission line in a weak field we determined, with the aid of (1) and (2), the value of the hole g-factor of an exciton bound with a neutral donor, $g_1 = 1.15 \pm 0.15$, which is close to the value of g_1 obtained in[7]. From the polarization of the TO emission line of this exciton we have obtained the value $\Phi_N = \Phi_{\mathrm{TO}} = -0.4$ to 0.5 for the transition with participation of a TO phonon. It is seen from Fig. 1 that the polarization of all the lines corresponding to transitions with TO-phonon emission is of the same sign. It follows from (1)—(3) that the agreement between the signs of the polarization of the TO emission lines of an exciton bound with a neutral donor, and an exciton bound with a neutral acceptor, can take place at equal signs of

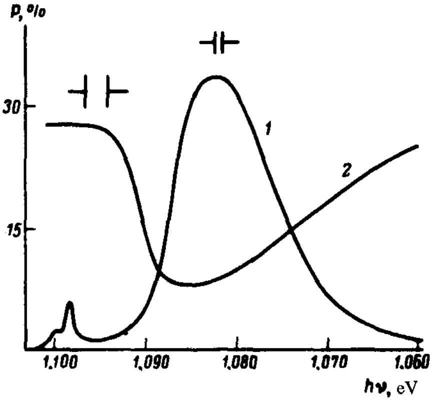

FIG. 2. Spectral distribution of the radiation and of the degree of circular polarization P in pure silicon ($\rho \sim 6500$ Ω cm, p-type), $T = 1.9$ °K: 1—emission, 2—polarization, $H = 46$ kOe.

g_1 and g ($g = 2$ according to[8]) only if the total angular momentum of the two holes is $I = 2$ for the ground state of the exciton bound with a neutral acceptor. The hypothesis that the state with $I = 2$ has the minimal energy was advanced in[9], but it appears that there were no experimental data to confirm this assumption prior to the present paper.

Figure 2 shows the spectral distribution of the polarization and of the emission in pure silicon at a high level of excitation. Using the depolarization factor determined from Fig. 1, we obtained from Fig. 2 the average degree of polarization of the 1.082-eV line. From this value, using (1) and (4), and putting $E_F^e = 8.2$ meV, $E_F^h = 16.0$ meV,[4], $g = 2$,[8] and $\Phi_{TO} = -0.4$, we calculated the g-factor of the hole in the condensate, namely $g_1 \approx 25$. This value greatly exceeds all the known experimental and theoretical values of the g-factors of free and bound holes in silicon.

Interaction between the carriers in the condensate can lead to an increase of the spin susceptibility of the electrons and holes[10] and accordingly to an increase of the degree of circular polarization of the radiation. The gain of the spin susceptibility for the electron Fermi liquid in a normal metal does not exceed 1.5 for $r_s < 1$.[10] Since $r_s \approx 0.84$ for Si in the condensate,[11] the cause of the appreciable enhancement (by more than one order of magnitude) of the spin susceptibility of the holes in the condensate is not clear.

Figure 3 shows the temperature dependence of the degree of polarization of the emission of free excitons and the 1.082-eV line. The temperature was determined by measuring the width of the emission line of the free electrons in the interval $6 \leq T \leq 15$ °K, and monitored in the interval $1.9 \leq T \leq 4.2$ °K against the ratio of the LO and TO components of the free-exciton emission,[12] and was equal to the temperature of the helium bath. With increasing temperature, the polarization of the free exciton decreases like $\sim 1/T$, and the polarization of the 1.082-eV line is constant at $1.9 < T < 10$ °K and decreases by an approximate factor 1.4 at $11 < T < 14$ °K. For the exciton condensate one should expect constancy of the polarization up to temperatures close to critical.

We note that the degree of polarization of the 1.082-eV line in a field ~ 50 kOe should correspond to about a 50% degree of orientation of the holes in the

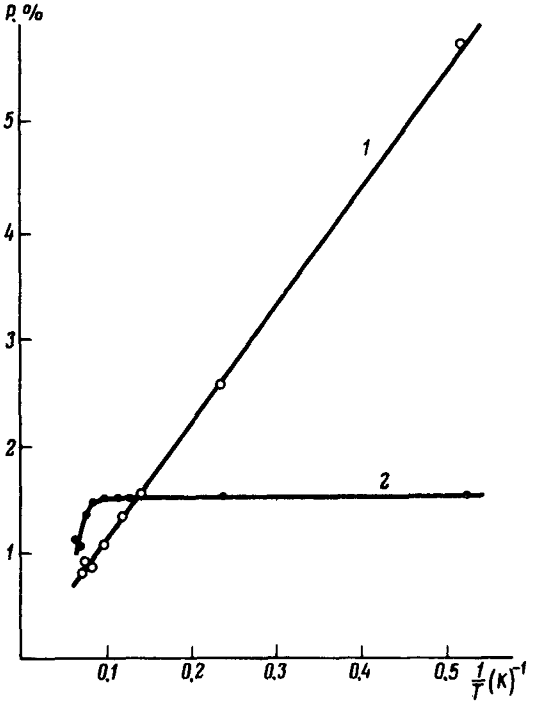

FIG. 3. Temperature dependence of the degree of circular polarization P of n-Si : P, $\rho \sim 100\ \Omega$ cm, $H = 6$ kOe; 1) free exciton, $h\nu = 1.098$ eV, TO phonon; 2) 1.082-eV line, $h\nu = 1.082$ eV, TO phono

condensate (the number of holes oriented along the field is approximately one-third the number of holes oriented against the field). In this case one could expect a noticeable change in the shape and width of the line. However, no changes in the line shape and in its position was observed in a magnetic field up to 50 kOe.

It is proposed in[3] that the 1.082-eV line is connected with emission of excitonic molecules. If the total angular momentum of the holes in the ground state of the molecules is $I = 2$, then the polarization of the biexciton radiation should have the same sign and should be close to the degree of polarization of the exciton emission. If it is assumed that the 1.082-eV line is connected with excitonic molecules, then the polarization of this line should agree approximately with the expected value. However, the explanation of the temperature dependence of the polarization in the model of the excitonic molecules encounters serious difficulties.

In conclusion, the authors thank A.G. Aronov, M.I. D'yakonov, and V.I. Perel' for useful discussions.

[1] R.I. Dzhioev, B.P. Zakharchenya, and V.G. Fleĭsher, Pis'ma Zh. Eksp. Teor. Fiz. 17, 244 (1973) [JETP Lett. 17, 174 (1973)].
[2] D. Bimberg and W. Ruhle, Proc. Twelfth Intern. Conf. on Physics of Semiconductors, Stuttgart, 1974, p. 651.
[3] J.R. Haynes, Phys. Rev. Lett. 17, 860 (1966).

A.S. Kaminskiĭ, Ya.E. Pokrovskiĭ, and N.V. Alkeev, Zh. Eksp. Teor. Fiz. **59**, 1937 (1970) [Sov. Phys.-JETP **32**, 1048 (1971)].

M.I. D'yakonov and V.I. Perel', Fiz. Tverd. Tela **14**, 1452 (1972) [Sov. Phys. Solid State **14**, 1245 (1972)].

V.M. Asinin, Yu.N. Lomasov, and A.A. Pogachev, Pis'ma Zh. Tekh. Fiz. **1**, 596 (1975) [Sov. Tech. Phys. Lett. 1, 268 (1975)].

J.M. Cherlow, R.L. Aggarwal, and B. Lax, Phys. Rev. **B7**, 4547 (1973).

G. Feher, Phys. Rev. **114**, 1219 (1959).

P.I. Dean, W.F. Flood, and G. Kaminskij, Phys. Rev. **163**, 721 (1967).

D. Pines and F. Nozieres, Theory of Quantum Liquids, Benjamin, 1965.

W.F. Brinkman and T.M. Rice, Phys. Rev. **B7**, 1508 (1973).

R.B. Hammond, D.L. Smith, and T.C. McGill, Phys. Rev. Lett. **35**, 1535 (1975).