Antiferromagnetic ordering of holes in doped silicon

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Polarization of the recombination radiation of Si:B in a magnetic field was studied. Antiferromagnetic ordering of holes was found in the range of acceptor concentrations $n_A \approx 1\times 10^{17}$–$3\times 10^{18}$ cm^{-3}. It is shown that at $n_A \approx 1\times 10^{17}$ cm^{-3} the excitons can be combined with clusters of one, two, or three impurities.

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It is known that the interaction of shallow impurities in semiconductors forms a band of impurity states. For impurity concentrations $n < n_c$, where n_c determines the Mott transition, the carrier states in the impurity band are localized.[1] According to the Mott model,[1] the ground state of the impurity band for $n < n_c$ is antiferromagnetic, because of exchange interaction of the carriers. In this state the spin moments of the carriers located at the nearest impurities are antiparallel, and the average spin moment of the carriers should be zero.

In this work the average projection of the spin moment of holes $\langle j_z \rangle$ in the direction of the magnetic field **H** was measured directly for the first time in boron-doped silicon with acceptor concentrations $n_A \approx 10^{17}$–10^{19} cm^{-3}. In order to determine the value of $\langle j_z \rangle$, a method based on measurement of the circular polarization of the recombination radiation in a magnetic field[2] was used. This method and the corresponding experimental procedure have been described in detail in Ref. 2. All the measurements were carried out in the Faraday geometry for **H** [111] and at a temperature $T = 1.9$ K. We found that for $n_A \approx 1 \times 10^{17}$–$3 \times 10^{18}$ cm^{-3}, smaller than n_c (in Si:B $n_c \approx 5 \times 10^{18}$ cm^{-3} [1]), $\langle j_z \rangle = 0$, which indicates antiferromagnetic ordering of holes in the crystal.

The emission and polarization spectra of the Si:B samples with different n_A are shown in Fig. 1. In these samples the average distance between the impurities is comparable with the radius of the bound exciton, and the electron-hole (*e-h*) pair excited by the light is bound to the group of nearest impurities. As the impurity concentration increases, the interaction potential between the *e-h* pair and the impurity atoms increases, and the absolute fluctuations of this potential also increases; this, in turn, shifts the emission line in the spectrum toward the longer wavelengths relative to that for the bound exciton, and it broadens the line (Fig. 1). The spectral position of the

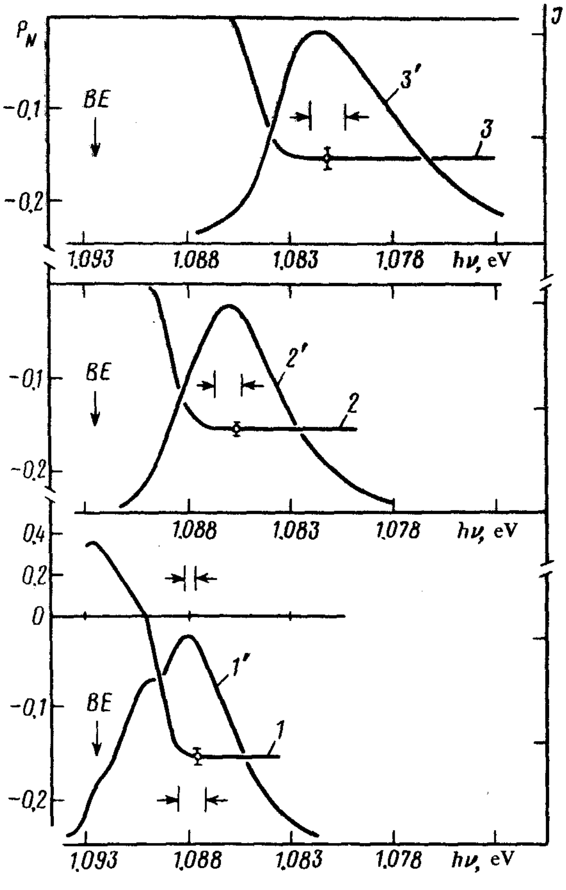

FIG. 1. Spectral emission distribution J(1', 2', 3') and circular polarization P_N(1, 2, 3) in Si:B in a magnetic field $H = 50$ kG at $T = 1.9$ K and an excitation level $I \sim 1$ W/cm^2 (*TO–LO* line): (1) 1', $n_A \approx 1 \times 10^{17}$ cm^{-3}; (2) 2', $n_A \approx 5 \times 10^{17}$ cm^{-3}; (3) 3', $n_A \approx 1 \times 10^{18}$ cm^{-3}. The arrow indicates the position of the *TO* emission line of the bound exciton at $n_A \approx 3 \times 10^{15}$ cm^{-3}.

emission line and its behavior with increasing n_A indicates that the emission is not related to the band—impurity transition, but is rather due to formation of an exciton-impurity band.

Figure 1 also shows that for $n_A \approx 1\times 10^{18}$ cm^{-3} and $n_A \approx 5\times 10^{17}$ cm^{-3} the emission polarization is negative, is almost independent of the photon energy, and is large in absolute value. Since the contribution of electrons and holes to the emission polarization in silicon has different signs,[2] according to Ref. 2, the large negative polarization is due to electron orientation in the magnetic field, while the contribution of the holes to polarization is zero, i.e., $\langle j_z \rangle = 0$ for the nearest group of holes with which the photoexcited electron combines. Since the projection of the moment of the hole can have four values $j_z = \pm 3/2, \pm 1/2$, this means that $\langle j_z \rangle = 0$ for the four nearest holes, including the three holes at the three impurity centers and one photoexcited hole. This antiferromagnetic ordering of the four nearest holes should occur in the sample even in the absence of photo-excitations of the *e-h* pair. If the antiferromagnetic ordering of the holes were absent and the localized holes were oriented independently of one another, $\langle j_z \rangle$ would not be equal to zero, and the emission polarization would have a positive sign and would agree in magnitude with the emission polarization of a bound exciton.

It should be noted that a decrease of the emission polarization to zero in a small spectral region of width 1–2 MeV at the short wavelength edge of the emission lines in the samples with $n_A \approx 1\times 10^{18}$ cm^{-3} and $n_A \approx 5\times 10^{17}$ cm^{-3} may be related according to Ref. 2, to the large contribution of the *LO* line to the *TO* emission line. In the case of the samples with $n_A \approx 1\times 10^{17}$ cm^{-3}, as seen in Fig. 1, the emission polarization in the long-wavelength part of the line is negative, coincides with the emission polarization of the samples with $n_A \approx 1\times 10^{18}$ cm^{-3}, $n_A \approx 5\times 10^{17}$ cm^{-3}, and is attributed to the contribution to the emission of the *e-h* pairs that are bound to clusters consisting of three impurities. The polarization in the short-wavelength region of the emission line for this sample is positive and agrees in sign with the polarization of the emission of the exciton bound to a neutral acceptor.[2] This means that the short-wavelength region of the emission line in this sample is due to *e-h* pairs that are bound to two impurities, as well as to one impurity. This interpretation of the emission spectrum of the sample with $n_A \approx 1\times 10^{17}$ cm^{-3} is confirmed by a structure comprised of three maxima in the spectrum in Fig. 1.

Figure 2 shows the dependence of the emission polarization P_N on the magnetic field. The dashed line for curve 2 (Fig. 2) shows the theoretical dependence $P_N = -\frac{1}{2}\Phi_N \operatorname{th}\left(\frac{1}{2g}\mu_0 H/kT\right)$ ($g = 2$, where g is the electron factor, μ_0 is the Bohr magneton, and $\Phi_N \approx 0.32$[2]), corresponding to the emission polarization for $\langle j_z \rangle = 0$. The dotted line for curve 3 shows the theoretical dependence for the *e-h* pair bound to two impurities. It can be seen that the theoretical dependences in Fig. 2 are in good agreement with the experimental dependences.

It is expected that the antiferromagnetism of the impurities is a universal effect in semiconductors. Thus, for example, the data in Ref. 3 for the negative magnetoresistance in *p*-InSb can be explained[3] as a consequence of the antiferromagnetic order.

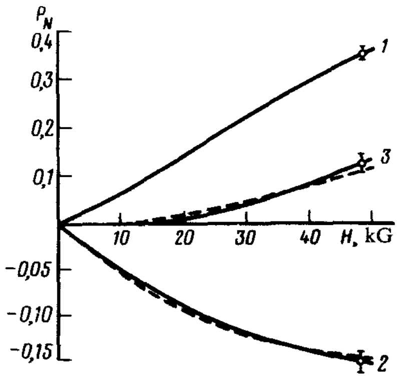

FIG. 2. Dependence of the circular polarization of emission P_N on the magnetic field H in Si:B at $T = 1.9$ K, $I \sim 1$ W/cm^2 (*TO–LO* lines): 1, $n_A \approx 3\times10^{15}$ cm^{-3} ($h\nu = 1.0925$ eV, bound exciton, *TO* line); 2, $n_A \approx 1\times10^{18}$ cm^{-3} ($h\nu = 1.081$ eV), $n_A \approx 5\times10^{17}$ cm^{-3} ($h\nu = 1.086$ eV, $n_A \approx 1\times10^{17}$ cm^{-3}) $h\nu = 1.087$ eV is the long-wavelength part of the line; 3, $n_A \approx 1\times10^{17}$ cm^{-3} ($h\nu = 1.091$ eV is the short-wavelength part of the line). The solid lines denote the experiment and the dashed lines denote the theory at $T = 1.9$ K, $g = 2$, $g_1 = 1.2$ [2] (g_1 is the g factor for the holes). The polarization observed experimentally is $P_{\rm exp} = DP_N$,[2] where $D \approx 0.7$.

It can be seen from the data in Fig. 3 that at $n_A \approx 5\times10^{17}$ cm^{-3}, the emission line is shifted toward longer wavelengths with increasing level of excitation I, the degree of emission polarization decreases, and the maximum in the polarization for large I occurs in the short-wavelength region of the line. It can be shown that the emission polarization due to orientation of the electrons can be observed in electron-hole drops (EHD) of small radius because of the dimensional effect that leads to a decrease in the number of quantum electron levels below the level of the Fermi electrons in the EHD. A similar variation of the emission polarization with increasing I can also be observed when the recombination radiation is a superposition of the emission of macroscopic EHD (for which $P_N \sim 10^{-2}$ [2]) and the emission from regions in

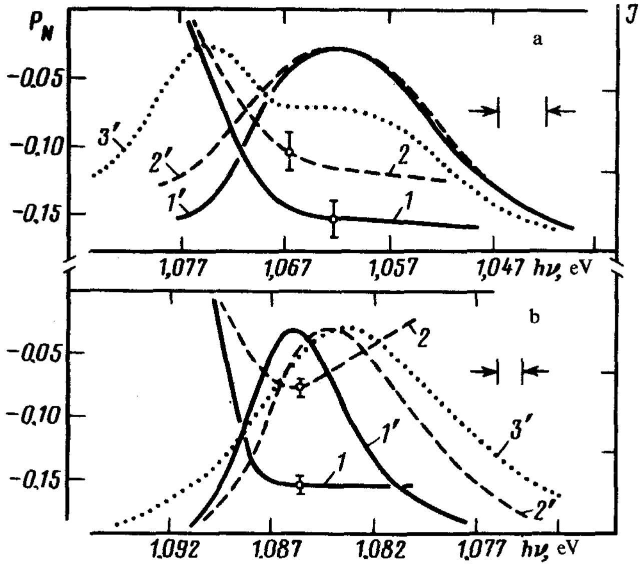

FIG. 3. Spectral distribution of the polarization P_N(1, 2) and emission J(1′, 2′, 3′) at different excitation levels I in Si:B in the field $H = 50$ kG at $T = 1.9$ K (*TO–LO* lines): (a) $n_A \approx 1\times10^{19}$ cm^{-3}; (b) $n_A \approx 5\times10^{17}$ cm^{-3}; (1, 1′) $I \sim 1$ W/cm^2; (2, 2′) $I \sim 10^2$ W/cm^2; (3′) $I \sim 10^3$ W/cm^2 (b: at $I \sim 10^3$ W/cm^2, $P_N = 0$).

the crystal with a small concentration of the *e-h* pairs, and also for a continuous increase of the density of the degenerated *e-h* plasma. The shift of the emission line with increasing n_A toward the longer wavelengths can be observed only at $n_A < 10^{18}$ cm^{-3}. At $n_A > 10^{18}$ cm^{-3}, the maxima of the emission lines are shifted toward the short wavelength region, and the emission polarization decreases slightly with increasing I (Fig. 3). This result means that the EHD in doped silicon can occur only at $n_A < 10^{18}$ cm^{-3}. The formation of EHD in the range $n_A \approx 10^{17} - 10^{18}$ cm^{-3} may be possible because of the motion of the *e-h* pairs along the impurities in the exciton-impurity band. The motion of the *e-h* pairs at these n_A requires a detailed investigation and is of great interest, since under the condition of antiferromagnetic ordering of the holes the photoexcited *e-h* pair moves as a spin polaron.[1]

[1] N.F. Mott, Perekhody metall-izolyator (Metal-Insulator Transitions), Nauka (1979).

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[3] S.A. Obukhov, *ibid.* **20**, 312 (1978) [*ibid.* **20**, 182 (1978)].