Anomalous spin susceptibility of holes in a strongly doped silicon

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The paramagnetic properties of holes in strongly doped Si:B at a temperature $T = 1.9$ K are investigated. An enhancement of the spin susceptibility of holes due to anomalously large spin magnetic moment of the holes near the Fermi surface was observed in the region of the Mott transition on the metallic side.

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One of the methods of investigating the Mott transition in the impurity band in semiconductors is based on measuring the spin susceptibility of electrons using EPR.[1-3] In the case of acceptor impurities, however, this method is impracticable. A method based on measurement of the degree of circular polarization of recombination radiation in a longitudinal magnetic field can be used to measure the spin susceptibility of holes.[4,5]

In this paper we use this method to investigate the impurity band in silicon doped with boron in the concentration range of the acceptors $n_A \approx (2\times 10^{18} - 8\times 10^{18})$ cm $^{-3}$, i.e., directly in the region of the Mott transition on the dielectric side and on

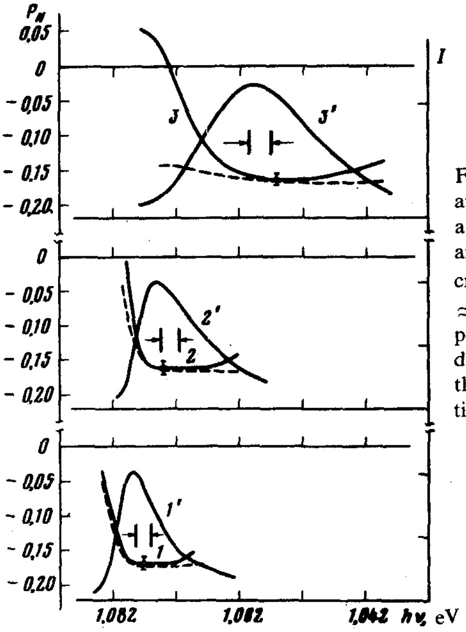

FIG. 1. Special distribution of radiation I (1′,2″,3′) and of the circular polarization P_N (1, 2, 3) in Si:B in a 50-kOe magnetic field at a temperature $T = 1.9$ K and $H_{\parallel}$ [111] (TO/LO lines). 1 and 1′, $n_A \approx 2.2\times 10^{18}$ cm^{-3}; 2 and 2′, $n_A \approx 3.6\times 10^{18}$ cm^{-3}; 3 and 3′, $n_A \approx 7.5\times 10^{18}$ cm^{-3}. The solid curves represent the experiment and the dashed curves denote the spectral distribution of the quantity $(1/2)\phi_N$ determined by the TO/LO splitting (calculation). The vertical sections indicate the error.

the metallic side (the concentration of the acceptors n_C in Si:B, which determines transition, is $n_C \approx 5\times 10^{18}$ cm^{-3} [1]). One of the virtues of this method is its ability to measure the spectral distribution of the average projection of the spin moment of the holes $\langle j_z \rangle$ in the direction of the magnetic field H in the impurity band.

Altukhov *et al.*[5] observed that at $n_A \approx (1\times 10^{17} - 3\times 10^{18})$ cm^{-3} and $\langle j_z \rangle = 0$ in Si:B in a $\leqslant$50-kOe field and $T = 1.9$ K, which indicates that the holes have antiferromagnetic ordering in the impurity band. The broad emission lines at such n_A are attributable to formation of the exciton-impurity band, and the quasi particle corresponding to this band is an exciton (a photoexcited *e-h* pair) which is bound in the group of the nearest impurities and facilitates antiferromagnetic orientation of the nearest holes, i.e., it produces a spin polaron.[1] As the estimates show, at $n_A \sim 10^{18}$ cm^{-3} the contribution from the exciton-impurity band to the energy width, which is associated with the transfer integral,[1] is comparable to the contribution induced by a chaotic distribution of impurities in the crystal; thus, it is conceivable that at $n_A \sim 10^{18}$ cm^{-3} the exciton states are not localized in Anderson's sense, and the excitons can move along the crystal.

The exciton-impurity band can exist when $n_A < n_C$. When $n_A > n_C$ a metallic conductivity appears in the crystal, the current carriers shield the Coulomb interaction between the electron and the hole, and at $n_A > n_C$ the Si:B radiation is due to the recombination of the free electrons and holes from the impurity band. In this case the emission spectrum at low excitation level represents the density of states of the holes in the impurity band, and the width of the emission lines is determined by the Fermi energy of the holes E_F^h.

Figure 1 shows the emission and polarization spectra of the TO/LO emission lines of the Si:B samples. First, we shall examine the data for $n_A < n_C$. As is known, the *TO* and *LO* lines in silicon are split in the spectrum into $E_{LO} - E_{TO} = 1.8$ meV, and the *LO* line is situated above the *TO* line with respect to energy. The intensity ratio of these lines is $I_{LO}/I_{TO} \approx 0.11$,[6] and the constants characterizing the radiation polarization have opposite signs ($\phi_{TO} = 0.40$ and $\phi_{LO} = -0.45$ [4]). Because of this, the value of $-(1/2)\phi_N$, which is equal to the degree of polarization of the *TO/LO* emission line in the $\leqslant$50-kOe field at $\langle j_z \rangle = 0$, depends on the energy of the radiation quantum $h\nu$; in this case, the average value of $-(1/2)\phi_N$ is $P_N^0 = -(1/2)\ \phi_N^0 \approx 0.16$.[4,5] The value of $-(1/2)\phi_N$, which is represented by a dashed curve in Fig. 1, is almost constant in the main part of the emission line and decreases in absolute value at the short-wave end. It can be seen in Fig. 1 that at $n_A \approx 2.2 \times 10^{18}$ cm^{-3} and $n_A \approx 3.6 \times 10^{18}$ cm^{-3} the theoretical curves almost coincide with the experimental curves; thus, for these n_A (near n_C on the dielectric side) $\langle j_z \rangle \approx 0$.

The *TO-LO* splitting is not significant for a broad emission line at $n_A \approx 7.5 \times 10^{18}$ cm^{-3}, and the quantity $-(1/2)\phi_N$ depends weakly on $h\nu$. However, the experimental curve for $n_A \approx 7.5 \times 10^{18}$ cm^{-3} (near n_C on the metallic side) differs greatly from the theoretical curve in the short-wave part of the emission line, and hence in this case $\langle j_z \rangle \neq 0$. We can show that at $|(P_N - P_N^0)/P_N^0| \ll 1$, where P_N is the average polarization of the emission line, the average moment of the holes in the impurity band and in the $\geqslant$50-kOe field is $\langle j_z \rangle \approx \alpha_N (P_N - P_N^0)/P_N^0$ (for the *TO/LO* line $\alpha_N \approx 0.78$). We determined from curves 3 and 3′ that at $n_A \approx 7.5 \times 10^{18}$ cm^{-3} $\langle j_z \rangle = -0.11$ in the 50-kOe field. For the degenerate holes in silicon, the Pauli paramagnetism gives $\langle j_z \rangle^P = -(15/8)\, g_1 (\mu_0 H / E_F^h)$,[4] where $g_1 \approx 1.2$,[4] g is the hole factor, and μ_0 is the Bohr magneton. At $n_A \approx 7.5 \times 10^{18}$ cm^{-3} $E_F^h \approx 25$ meV in silicon and $\langle j_z \rangle^P \approx -0.027$ in a 50-kOe field. Therefore, the force factor of the spin susceptibility of the holes at $n_A \approx 7.5 \times 10^{18}$ cm^{-3} is $\chi_h / \chi_h^P = \langle j_z \rangle / \langle j_z \rangle^P \approx 4$, where χ_h^P is the Pauli susceptibility and χ_h is the observed susceptibility. This appreciable enhancement of the susceptibility is attributable to anomalously large magnetic moment of the holes near the Fermi surface, since a significant variation of radiation polarization is observed in the short-wave part of the line. In fact, the spectral distribution of $\langle j_z \rangle$ in the impurity band represents the difference between the experimental and the theoretical curve, and we can determine from curve 3 in Fig. 1 that the magnetic moment of the holes near the Fermi surface exceeds the value determined by the Pauli paramagnetism by more than an order of magnitude.

An enhancement of the spin susceptibility of electrons, which was interpreted as a consequence of the existence of localized moments in metallic samples, was observed earlier in the EPR studies of Si:P.[2,3] This viewpoint was confirmed subsequently by Sasaki *et al.*[7] and Kamimura.[8] As shown in Ref. 1, the singly occupied, localized states, which contribute to the enhancement of the spin susceptibility, must be located near the Fermi surface; thus, the hypothesis of the existence of localized moments is consistent with the results of this study. There is, moreover, another point of view,[1,9,10] according to which the enhancement of the spin susceptibility may be associated with the strongly correlated Brinkman and Rice gas,[9] and the question which of these mechanisms produces anomalously large magnetic moment of the holes near the Fermi surface requires a more thorough examination.

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