Anderson transition in the exciton-impurity band in silicon

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An Anderson transition is observed in the exciton-impurity band (EIB) in Si:P with donor concentration $n_D = n^\circ \simeq 1.5 \times 10^{17}$ cm^{-3}. The transition is accompanied by a sharp rearrangement of the recombination-radiation spectrum of EIB with increasing n_D in the region $n_D \simeq n^\circ$ due to increased exciton mobility and a change in the polarization of radiation in a magnetic field.

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In silicon, doped with fine impurities, most of the excitons are bound to impurity atoms at low temperatures and low levels of excitation. In addition, in the range of impurity concentrations $n \sim 10^{14}$–10^{16} cm^{-3}, excitons are bound on isolated impurities and are observed in the recombination radiation spectrum as narrow lines of the bound exciton. In the region $n \sim 10^{17}$–3×10^{18} cm^{-3} in Si:B and Si:P the average distance between impurities $R_0 = (4\pi/3n)^{-1/3}$ is comparable to the radius of the bound exciton $a \approx 4 \times 10^{-7}$ cm, while the energy of interaction of the exciton with the surrounding impurity atoms and the magnitude of the transfer integral $I \sim 2\epsilon_0 e^{-R/a}$, where $R \sim R_0$ is comparable to the binding energy of an exciton on an impurity $\epsilon_0 \approx 5$ meV.[1] At such impurity concentrations, the interaction of excitons and impurities leads to the formation of an exciton bound state and an impurity band: exciton-impurity band (EIB).[1] Excitons in EIB are bound to groups of impurity atoms and are manifested in the recombination radiation spectrum as broad lines, which with increasing n broaden and shift toward lower energies[1] (Fig. 1).

Just as for an atomic system with structural disorder, the magnitude of fluctuations in the potential V for excitons in EIB must increase more slowly with increasing n than with the width of the EIB $B \sim 2zI$, where $z \approx 2^2$ which leads to the possibility of observing an Anderson transitions[3,4] in EIB for some impurity concentration n° for which the width of the EIB B is comparable to V.[2] In the region $n < n^0$, all states in EIB are localized and the motion of excitons along impurities is in the form of thermally activated hops. In the region $n > n^0$, in addition to localized states situated in the spectrum at the edges of the EIB, the EIB also includes distributed states,[3,4] which lead to activationless motion of excitons along the impurities due to the transfer integral. For $n < n^0$, the motion of excitons slows down with decreasing temperature T and at $T = 0$ there is no diffusion of excitons. For $n > n^0$ and $T = 0$, the presence of distributed states in EIB leads to the appearance of exciton diffusion. Thus the Anderson transition in EIB must lead to a sharp increase in the exciton mobility at low temperatures due to the appearance of distributed states. Since the rate of relaxation of exciton energy in EIB is related to the motion of excitons along impurity atoms, this transition in EIB must also be accompanied by a sharp increase in the energy relaxation rate of excitons.

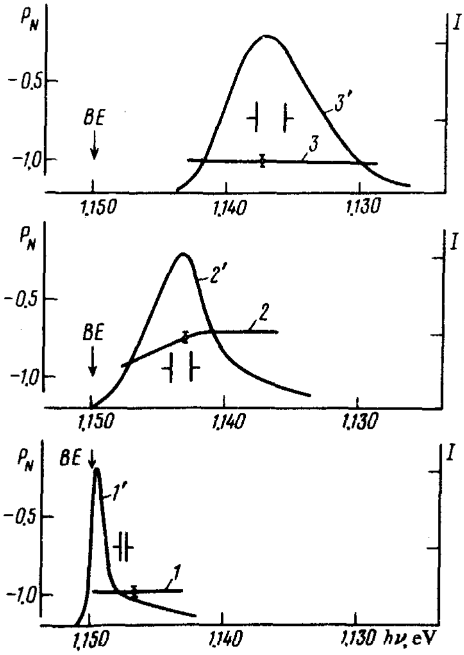

FIG. 1. Spectral distribution of radiation I(1'–3') and the degree of polarization P_N (1–3) in Si:P in a magnetic field $H = 50$ kG at temperature $T = 1.9$ K and $H \parallel [1,1,1]$ (NP line, Faraday geometry). 1,1'—$n_D \simeq 7.5\times10^{16}$ cm^{-3}; 2,2'—$n_D \simeq 2\times10^{17}$ cm^{-3}; 3,3'—$n_D \simeq 9.4\times10^{17}$ cm^{-3}. Excitation level ~0.5 W/cm^2.

In this work, we observed an Anderson transition in EIB in Si:P with donor concentrations $n_D = n^0 \simeq 1.5\times10^{17}$ cm^{-3}, while studying the recombination radiation spectra of EIB (Figs. 1 and 2) and the circular polarization of radiation in a longitudinal magnetic field (Figs. 1 and 3). The critical concentration n_0 satisfies the condition $(n^0a^3)^{1/3} \approx 0.2$. At $T = 1.9$ K the position of the maximum in the radiation of EIB is sharply displaced toward lower energies (Figs. 1 and 2) with increasing n_D in the region $n_D \approx n^0$. This displacement is related to the appearance of distributed states in the EIB with $n_D > n^0$ and to the appearance of activationless motion of excitons along the impurities, which in turn leads to an increase in the energy relaxation rate of excitons and predominant filling of the lower energy levels of the localized states. For $n_D \simeq 7.5\times10^{16}$ cm^{-3}, all states in EIB are localized, the excitons are bound on groups of small numbers of impurities, primarily consisting of one or even two impurities, and the maximum of the EIB radiation line in the spectrum is close to the position of the bound exciton radiation (Fig. 1). In the region $n_D \simeq 2\times10^{17}$–$10^{18}$ cm^{-3} the excitons are bound on groups consisting of a larger number of impurities and more closely situated impurities. With the increase of n_D in this region, the average number of impurities in such groups increases, while the average distance between impurities decreases, which further shifts the spectral radiation line toward lower energies (Figs. 1 and 2).

The existence of an Anderson transition in EIB is confirmed by the temperature

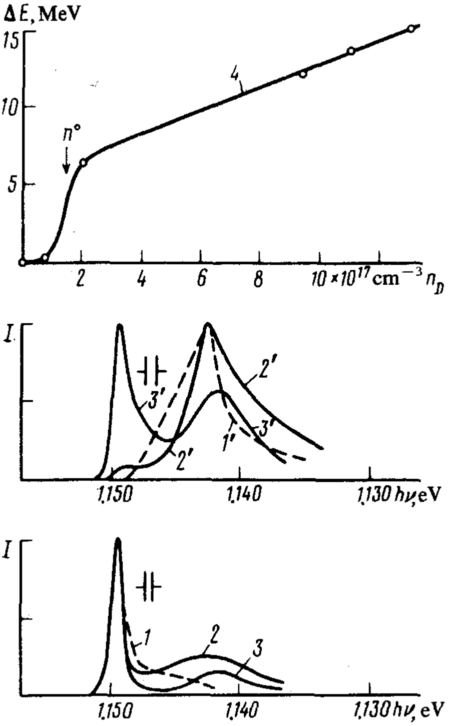

FIG. 2. The spectral position of the maximum of the EIB radiation line E as a function of the concentration n_D at $T = 1.9$ K (4) and the temperature dependences of the EIB radiation spectra in Si:P (1–3, 1′–3′) (NP line). 1,2,3—$n_D \simeq 7.5\times10^{16}$ cm^{-3}; 1′,2′,3′—$n_D \simeq 2\times10^{17}$ cm^{-3}; 1,1′ (dashed line) $T = 1.9$ K; 2,2′—$T = 17$ K; 3,3′—$T = 28$ K. $\Delta E = h\nu_0 - h\nu_M$ where $h\nu_0 = 1.150$ eV is the spectral position of the NP bound-exciton emission line, $h\nu_M$ is the spectral position of the maximum of the EIB emission line.

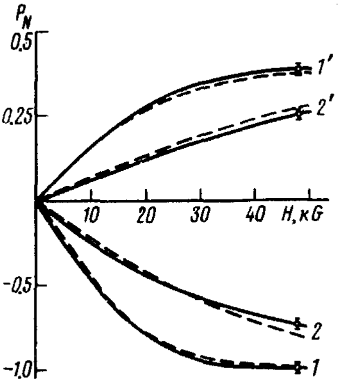

FIG. 3. Dependence of the degree of circular polarization of P_N radiation on the magnetic field H in Si:P at $T = 1.9$ K, $H \| \rangle 1,1,1]$ in Faraday geometry at the maxima of the radiation lines (NP line 1 and 2; *TO/LO* line 1′ and 2′). 1,1′—Bound exciton, $n_D \simeq 2\times10^{15}$ cm^{-3}; EIB, $n_D \simeq 9.4\times10^{17}$ cm^{-3}. 2,2′—EIB, $n_D \simeq 2\times10^{17}$ cm^{-3}. Dashed lines: 1,1′—Theory for a bound exciton with $\langle s_z\rangle = 0, g_l = 1{,}2, T = 1.9$ K; $\Phi_{\rm NP} = -1$, $\Phi_{TO/LO} = 0.32$.[5] Dashed lines: 2,2′—Theory for EIB with $\langle S_z\rangle \neq 0, g_1 = 0.9, g = 2, T = 1.9$ K, $\Phi_{NP} = -1$, $\Phi_{TO/LO} = 0.32$.[5]

dependence of the radiation spectra in Fig. 2. For $n_D \simeq 7.5 \times 10^{16}$ cm^{-3}, as the temperature increases, the probability of thermally activated hops increases, which increases the radiation intensity of the lower energy levels of EIB. The opposite temperature dependence occurs in the region $n_D.n^0$. As the temperature increases, in this region of n_D the radiation intensity from higher energy states increases in accordance with the temperature change in the Boltzmann distribution. It should be noted that the change in the EIB radiation is observed for $T > 10$ K. When T increases from 1.9 to 5 K, there are no appreciable changes in the EIB radiation spectra, which indicates the extremely small probability for thermally activated hops in the region $n_D < n^0$ at $T < 5$ K.

It is evident from Figs. 1 and 3 that the degree of polarization of radiation in a magnetic field with $n_D \simeq 7.5 \times 10^{16}$ cm^{-3} is approximately equal to the degree of polarization of bound exciton radiation and, therefore, the average momentum of electrons in EIB, with which nonequilibrium holes recombine is close to zero for $n_D < n^0$ $(\langle s_z \rangle = 0)$.[5] Nevertheless, the degree of polarization at the maximum of the radiation line for $n_D \simeq 2 \times 10^{17}$ cm^{-3} differs greatly from the degree of polarization of bound exciton radiation. This result can be explained by the fact that at $n_D \simeq 2 \times 10^{17}$ cm^{-3} the number of impurities in the groups on which excitons are bound is quite high, but the interaction of electrons localized on different impurities is small; electrons in such groups are oriented in a magnetic field as free electrons $(\langle s_z \rangle \neq 0)$ and are characterized by a spin Curie susceptibility. In addition, the observed polarization of radiation is close to the polarization of a free exciton,[5] calculated for the case $g_1 = 0.9$ and $g = 2$, where g_1 is the hole g factor and g is the electron g factor (Fig. 3). For $n_D \sim 10^{18}$ cm^{-3}, the exchange interaction of electrons in the impurity band greatly decreases the electronic spin susceptibility[1,4] and the observed polarization of radiation, just as for $n_D < n^0$, is close to the polarization of bound exciton radiation (Figs. 1 and 3).

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