Zeeman splitting in the emission spectra of multiparticle exciton-impurity complexes in silicon

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The observed picture of the Zeeman splitting of the emission lines of multiparticle exciton-impurity complexes (E_mIC) in undeformed and uniaxially deformed silicon doped with phosphorus confirms the shell model of the E_mIC.

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The recombination spectra of indirect semiconductors containing shallow impurity centers contain, at sufficiently high excitation densities and low temperatures, a series of narrow lines. This line structure was first observed in silicon crystals doped with boron and was interpreted as the result of exciton emission in a multiparticle exciton-impurity complex E_mIC (where m is the number of excitons bound with the center).[1] To explain the nature of the E_mIC, a shell model (SM) was recently proposed.[2] According to this model, the electrons and holes in the multiparticle complex fill successively the shells in accordance with the Pauli principle. Owing to the band degeneracy, the number of single-particle electronic states in the complex, which are characterized by the principal quantum number, increases in accord with the multiplicity of the degeneracy. The shell model makes it possible to classify the electronic states of the complex by symmetry types, and predicts the number of lines in the recombination spectra and their fine structure. The SM describes well the singularities of the emission spectra of E_mIC in silicon which has not been subjected to external action,[3,4] as well as in uniaxially deformed crystals.[5] In particular, it was shown in[5] that band degeneracy is a necessary condition for the formation of E_mIC in silicon.

One way of directly checking on the SM is to investigate the E_mIC spectra in a magnetic field. Within the framework of this model, the phononless emission lines (α lines) of the E_mIC on a neutral donor correspond to recombination of electrons from an inner Γ^1 shell that is doubly degenerate in spin. In a magnetic field, the number of Zeeman components for α lines, with allowance for all the allowed transitions between the spinsplit states, should remain constant. This does not contradict the experimental observations under conditions when the level splitting $g\mu H \approx kT$.[6] It is more advantageous to compare the Zeeman-splitting spectrum of the E_mIC with the splitting picture that follows from the SM representations, when the spin-excited states are not populated.

In the present study we investigated the emission spectra of E_mIC in silicon with donor impurity at 1.8 K in sufficiently strong magnetic fields, when the splitting is $g\mu H \gtrsim 3kT$. Owing to the strong difference between the intensities of the Zeeman components, due to transitions from the ground and excited states, the interpretation of the results becomes unambiguous under these conditions. In addition, we investigated the emission of the E_mIC in uniaxially deformed silicon in fields corresponding to

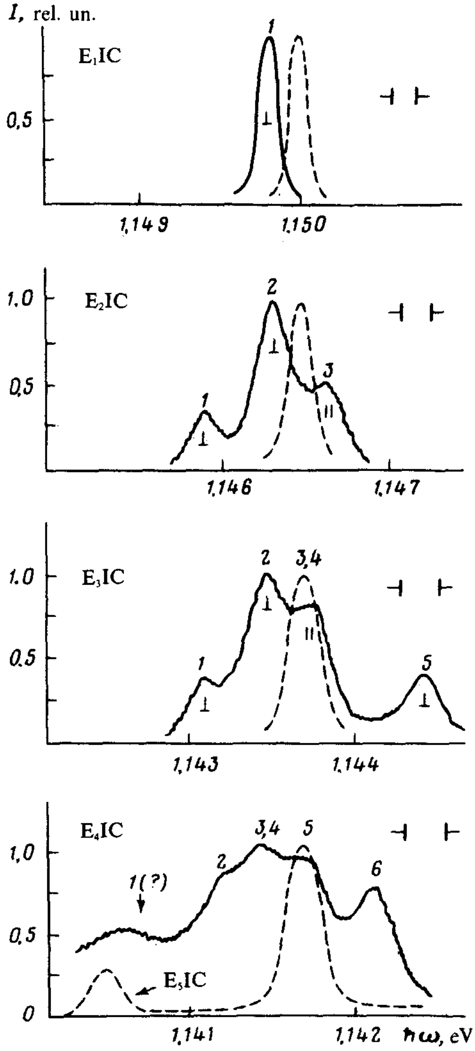

FIG. 1. Splitting of phononless emission lines of E$_m$IC in undeformed Si(P) crystals at $T=1.8$ K and $H=62$ kOe. H∥[111] and H⊥k. The dashed lines show the E$_m$IC spectrum corresponding to $H=0$. The radiation polarized along and across **H** is marked by the symbols ∥ and ⊥.

$g\mu H=(1\text{–}3)kT$. The lifting of the degeneracy in the valence band under the influence of the deformation simplifies appreciably the picture of the Zeeman splitting.

We used Si samples doped with phosphorous ($N_p=2\times10^{14}$ cm^{-3}). The excitation was with an argon laser, and the radiation was registered with a cooled photomultiplier with an S-1 cathode, operating in the photon-counting regime. The magnetic field was directed along the [111] axis, the radiation was registered in the Voigt configuration (**H**⊥**k**). The spectra for the four α lines in undeformed Si at 1.8 K and $H=62$ kOe are shown in Fig. 1.

According to the SM, the α lines correspond to recombination of an electron from the inner shell Γ^1 with a hole of symmetry Γ^8. The wave function of the system of electrons and holes is approximated in the SM by an antisymmetrical product of

TABLE I. Allowed α transition in a magnetic field for E$_m$IC in Si(P) according to the shell model[1].

Number of pairs in E$_m$IC	Initial state s_z	Initial state j_z	Final state s_z	Final state j_z	Polarization	Number of lines in spectrum
	undeformed Si(P)					
1	1/2, −1/2	−3/2	−1/2		$\perp$	1
			1/2	−3/2	$\perp$	1
2	1/2, −1/2	−1/2, −3/2	−1/2	−1/2	$\perp$	2
			−1/2	−3/2	$\parallel$	3
			1/2	1/2, −3/2	$\perp$	1
			−1/2	1/2, −1/2	$\perp$	2
3	1/2, −1/2	−1/2, 1/2, −3/2	1/2	−1/2, −3/2	$\parallel$	3
			−1/2	1/2, −3/2	$\parallel$	4
			−1/2	−1/2, −3/2	$\perp$	5
			1/2	1/2, −3/2, 3/2	$\perp$	1
			−1/2	1/2, −1/2, 3/2	$\perp$	2
4	1/2, −1/2.	−1/2, 1/2, −3/2, 3/2	1/2	−1/2, −3/2, 3/2	$\parallel$	3
			−1/2	1/2, −3/2, 3/2	$\parallel$	4
			1/2	−1/2, 1/2, −3/2	$\perp$	5
			−1/2	−1/2, −3/2, 3/2	$\perp$	6
	Deformed Si					
1	1/2, −1/2	−1/2	1/2		$\perp$	1
			−1/2		$\parallel$	2
	1/2, −1/2	1/2	1/2		$\parallel$	3
			−1/2		$\perp$	4
			1/2	1/2	$\perp$	1
2	1/2, −1/2	−1/2, 1/2	−1/2	1/2	$\parallel$	2
			1/2	−1/2	$\parallel$	3
			−1/2	−1/2	$\perp$	4

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[1] Only the splitting in the hole $\Gamma^8(\Gamma^4)$ and electron Γ^1 shells is indicated in Table I, since particles from only these shells participate in the recombination.

single-particle wave functions.[2] The probabilities of the different transitions are expressed in this case in terms of the known recombination rates of the individual electrons and holes.[2,7] The recombination of the electrons and holes with angular momentum projections s_z and j_z is forbidden in the case of a change $\Delta(s_z+j_z)\geqslant 2$. In the configuration **H**$\perp$**k**, the radiation produced upon recombination of an electron and a hole with the change $\Delta(s_z+j_z)=\pm 1$, is polarized in a plane perpendicular to the magnetic field, and at $\Delta(s_z+j_z)=0$ it is polarized along the field.[7]

The possible transitions from the ground state for E_mIC($m=1$–4) in the case of undeformed Si are listed in Table I. It is seen that the experimentally observed number of Zeeman components in the E_mIC lines, and their polarization agree well with those expected in the framework of the SM. The emission lines corresponding to recombination of electrons having $s_z=\pm 1/2$ with holes having $j_z=\pm 1/2$ cannot be resolved because of the close values of the g-factors g_e and $g_{h\ 1/2}$. The component corresponding to the transition 1 is not resolved in the E_4IC spectrum. We note, however, that the Zeeman components of the E_5IC line are superimposed in the corresponding region of the spectrum.

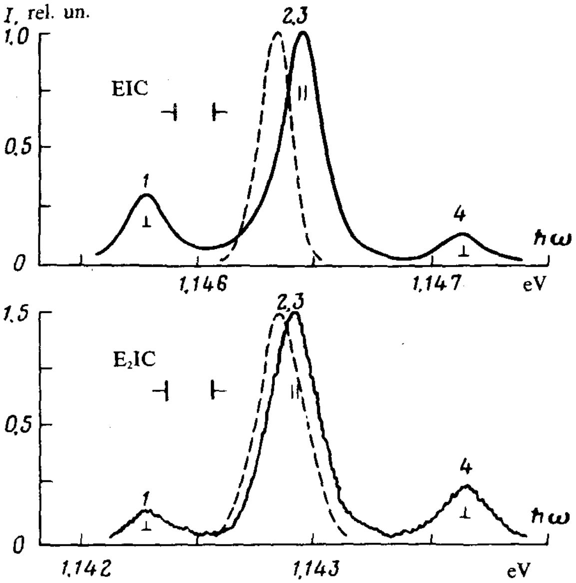

FIG. 2. Splitting of phononless emission lines of E_mIC in deformed Si(P) crystals at $T=1.8$ K, $H=62$ kOe, **H**||[111], **P**||**H** and $P=10$ kg/mm². The dahsed line shows the E_mIC spectrum at $H=0$ and $P=10$ kg/mm².

The picture of the splitting of the E_mIC level in the magnetic field becomes greatly simplified in deformed Si. Under conditions of strong uniaxial deformation the complexes produced in Si have only one or two bound exciton.[5] At a pressure **P**||[111], the conduction band remains unchanged, and the valence band splits into two bands that are doubly degenerate in spin. In strongly deformed Si, the holes in the E_mIC fill the shell Γ^4 which is doubly degenerate in spin ($J_z=\pm 1/2$). The spectra of the Zeeman splitting of E_1IC and E_2IC are shown in Fig. 2, and the transitions that are allowed by the SM are listed in Table I. The components corresponding to transitions 2 and 3 cannot be resolved because of the close values of the g-factors of the electrons and holes. The polarization of the components corresponds to that expected within the framework of the SM. In accordance with the SM, the intensity of line 4 in E_1IC decreases with increasing splitting of the ground state, whereas in E_2IC the intensity ratio of components 1 and 4 remains unchanged. An unexpected fact was that the ratio of the intensities of the Zeeman components 4 and 1 for E_1IC and E_2IC exceeded noticably the expected value (this ratio in E_1IC is determined by the factor $\exp(-g\mu H/kT)$, and in E_2IC the intensities of the components 1 and 4 should coincide). The possible cause of this anomaly is masked in the case of E_1IC by the fact that the spin sublevels of the deformed Si crystals are not in equilibrium.

Thus, the shell model provides in the main a good description of the experimentally observed Zeeman splitting in the spectra of multiparticle exciton-impurity complexes in deformed and undeformed silicon. We note in conclusion that the g factors obtained from the emission line splittings for the electrons and holes turn out to be the same within the limits of measurement error for all complexes, namely:

$$g_e = 1.9 \pm 0.1;\ g_{h\,1/2} = 1.7 \pm 0.2\ \ g_{h\,3/2} = 1.1 \pm 0.2.$$

These values agree with those determined in[8] for bound excitons in Si doped with As, but differ from the g factors of electrons bound with a donor and holes bound with an acceptor ($g_e = 2.0$; $g_{h\,3/2} = g_{h\,1/2} = 1.2$).[8]

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