A. S. Kaminskiĭ, V. A. Karasyuk, and Ya. E. Pokrovskiĭ. *Multiparticle exciton-impurity complexes in semiconductors.* In an ideal crystal lattice the electrons and holes can be considered as almost free particles similar to electrons and positrons in free space. The difference is that electrons and holes are characterized by an effective mass which can differ considerably from the mass of the free electron and which can have a strong anisotropy. In addition, the electrostatic interaction between the charged particles can be weakened greatly as the result of the high dielectric permittivity of the crystals. This leads to a change of the characteristic scales of distances and of the energies of bound states of electrons and holes. Proceeding from the analogy between electrons and holes and elementary particles, and taking into account the various possibilities in the ratios of their effective masses, Lampert[1] in 1958 predicted the possibility of existence in semiconductors of a number of mobile and immobile electron-hole complexes, some of which have since been observed experimentally. In particular, he predicted the existence of a bound exciton arising in capture of a free exciton by a neutral donor or acceptor. In 1960 Haynes[2] experimentally observed bound excitons in silicon doped with elements of groups III or V, on the basis of the appearance of narrow luminescence peaks arising on annihilation of an electron and a hole in a bound exciton. In 1970 Kaminskiĭ and Pokrovskiĭ[3] in a study of the photoluminescence of boron-doped silicon at 4.2 K observed a series of emission peaks which were excited successive as the level of excitation was increased. The origin of these peaks was explained by capture of several (m) excitons in boron atoms, as a result of which there arises a collective state which contains a singly charged impurity ion, m carries (electrons or holes) of the same sign of charge as in the impurity ion, and $m + 1$ carriers with the opposite sign of charge. These states received the name multiparticle exciton-impurity complexes.

According to the shell model proposed by G. Kirczenow in 1977 the electrons and holes in complexes occupy shells, the wave functions in which have the degeneracy order and symmetry of the wave functions of the simple donor and acceptor. For example, two electrons in complexes bound to donors of group V and silicon occupy a shell close to the impurity ion. Then there is a fourfold-degenerate hole shell, beyond which are located electron shells containing up to ten electrons. Thus, as a result of the high order of degeneracy it is possible in semiconductors to have complexes containing a large number of electrons and holes. In the case of electrons and positrons, the lowest state of which is degenerate only in spin, the existence of similar complexes is impossible. On recombination of a hole with an electron from the inner shell, lines of the α series are emitted, and on recombination with an external electron the shorter-wavelength β series is emitted. These series are observed experimentally (see for example Refs. 5 and 6). For uniaxial deformations (compression) of silicon the fourfold-degenerate hole shell is split into two doubly degenerate shells. This leads to a doubling of the luminescence lines, and for large deformations it leads to disappearance of complexes containing more than two holes.[7] Uniaxial deformation leads also to polarization of the radiation of the complexes. The polarization has been calculated on the basis of the wave-function symmetry predicted by the shell model and has turned out to be in good agreement with experiment.[8]

In perfect silicon crystals it has been possible by the method of interference spectroscopy to resolve the fine structure of the emission lines of complexes, including those with various uniaxial deformations. The main features of the fine structure have been interpreted on the assumption that it is determined by pairing of the angular momenta of the holes and by the exchange interaction of holes with electrons of the outer shells.[9,10] In addition it has been shown that one of the electrons in complexes bound to donors is localized near the impurity ion just as strongly as in the case of a neutral donor.

Spectral analysis of the luminescence of multiparticle exciton-impurity complexes permits easy determination of the content of elements of groups III and V even in the purest silicon crystals.[11]

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