Excitons bound to a surface-charge layer in silicon

P. D. Altukhov, A. A. Bakun, A. V. Krutitskiĭ, A. A. Rogachev, and G. P. Rubtsov

A. F. Ioffe Physicotechnical Institute, Academy of Sciences of the USSR, Leningrad

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A new emission line has been observed in the recombination-radiation spectra of silicon metal-oxide-semiconductor structures at a low surface-charge density. This line results from excitons which are bound to the layer of surface charge.

When excitons are bound to the layer of surface charge at a silicon surface in a metal-oxide-semiconductor structure, a 2D electron-hole (*e-h*) system forms. This system consists of a 2D layer of majority carriers (the first layer) and an additional 2D layer, less dense and further from the surface, consisting of nonequilibrium carriers of the opposite sign (the second layer).[1/2] The formation of a system of this sort gives rise to a new line in the recombination radiation: an S line.[1,2] If the surface charge density n_s is large, the repulsion of the *e-h* pairs associated with the spatial separation of the electron and hole layers causes the surface pairs to exist in the form of a 2D plasma with a density of pairs which increases with increasing excitation level. With increasing density of pairs, we observe a short-wave shift of the S line in the emission (Fig. 1). The magnitude of this shift is equal to the repulsive potential. We also observe an increase in the carrier conductivity in the second layer.[2] At small values of n_s, under the experimental conditions of Ref. 2, the surface pairs exist in the form of electron-hole droplets associated with a layer of surface charge. The critical value of n_s —that which separates the region in which there is a surface plasma from that in which there are surface electron-hole droplets — is $n_s^0 \approx 10$ cm^{-2} in the case of the [100] hole layer of surface charge.[2]

The attraction of electrons to the hole layer in the region in which the 2D plasma exists, at a low pair density, results from an electron-hole correlation interaction. An electron in the second layer induces a positive collective charge in the hole layer; this charge attracts an electron to the surface. At large values of n_s, the interaction of an electron with the hole layer at a large distance from the surface can be described approximately by an image potential.[1] Under these conditions, the screening of the Coulomb interaction of the electrons and holes by holes may prevent the formation of an excitonic-binding state of an electron from a second layer with an additional (non-equilibrium) hole from the first layer. In this case the spectral position of the S line can be described satisfactorily by a theory which ignores exciton effects. At sufficiently small values of n_s, however, at which the exciton radius a_B becomes smaller than the average distance between holes in the first layer, $n_s^{-1/2}$, the formation of excitons associated with the surface-charge layer becomes possible because of a decrease in screening. This case was studied theoretically in Ref. 3, where it was shown that an energy that binds excitons to the surface-charge layer exists even at small values of n_s. The extreme position of the surface emission line in the spectrum at small values of n_s

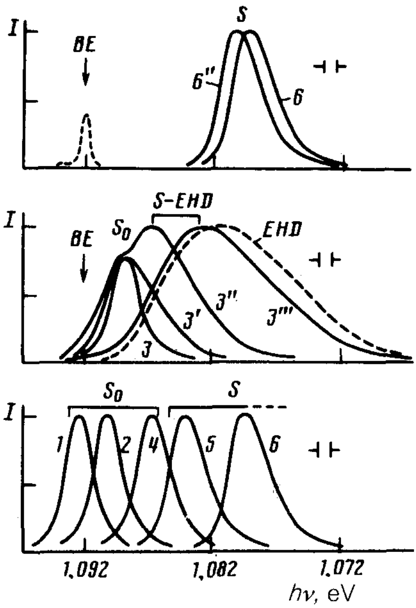

FIG. 1. Spectrum of the recombination radiation of silicon, I, at the temperature $T = 1.9$ K {metal-oxide-semiconductor structure; [100] hole layer; *TO-LO* lines; maximum carrier mobilities of $\mu_e = 1.05\times10^4$ $cm^2/(V\cdot s)$ and $\mu_h = 2.4\times10^3$ $cm^2/(V\cdot s)$ in the electron and hole surface-charge layers}. The surface-charge (hole) densities, n_s, in units of reciprocal square centimeters, are: 1—0; 2—1.6×10^{11}; 3—3‴ − 3.1×10^{11}; 4—5.3×10^{11}; 5—1.0×10^{12}; 6—6″ − 2.1×10^{12}. The excitation levels I_p, in units of watts per square centimeter, are: 1—6 − 2×10^{-4}; 3′—3×10^{-3}; 3″, 6″—4×10^{-2}; 3‴—3.

is the position of the exciton line in the interior of the semiconductor, and the nature of this line changes radically.

The excitons bound to the surface-charge layer should be observed at $n_s < n_s^0$ in the form of a surface gas phase, which coexists with surface electron-hole droplets, and they may be manifested in the recombination radiation spectra, as a line on the short-wave side of the line of surface electron-hole droplets. We observed a line of surface excitons (the S_0 line in Fig. 1) in the emission spectra of metal-oxide-semiconductor structures with a long lifetime of surface pairs in the region $n_s < n_s^0$ during the formation of a [100] hole layer. The intensity of the S_0 line increases slower than linearly with increasing excitation level, and it dominates the spectrum at low excitation levels. In this case there are no bulk lines of bound excitons. With $n_s = 0$, this line is caused by excitons bound to surface centers. With increasing n_s, the S_0 line shifts in the long-wave direction in the spectrum, and at $n_s < n_s^0$ it becomes the S emission line. This spectral position of the S_0 line agrees with the results of theoretical calculations.[3] Its spectral width is substantially less than the width of the emission line of surface electron-hole droplets and is determined by fluctuations in the surface potential. This circumstance distinguishes it from the S line, whose spectral width is determined by the Fermi energy of the holes at a low pair density. As the excitation level is raised, a line of surface electron-hole droplets appears on the long-wave side of the surface-exciton line in the emission spectrum. This new line broadens, shifts in the long-wave direction, and gradually converts into the emission line of bulk electron-hole droplets as a result of an increase in the size of the surface droplets.

This interpretation of the S_0 line is supported by the results of a study of the circular polarization of the emission in a magnetic field directed perpendicular to the

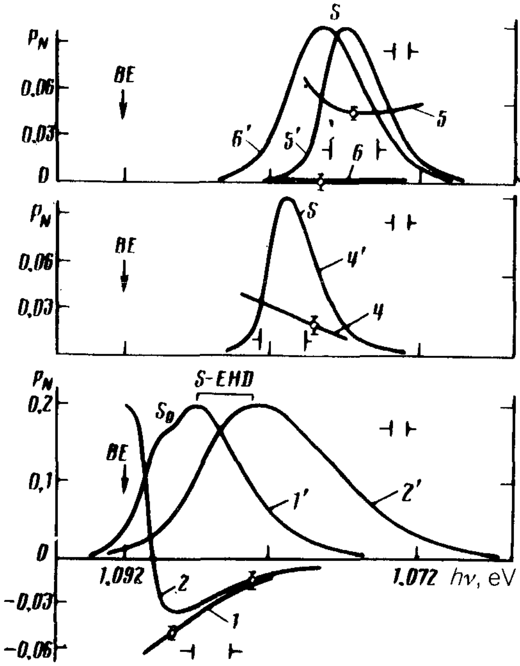

FIG. 2. Spectrum of the emission (1′–6′) and degree of circular polarization, P_N (1–6), of a metal-oxide-semiconductor at a temperature $T = 1.9$ K in a magnetic field $H = 50$ kOe, directed perpendicular to the [100] surface (*TO-LO* lines; Faraday geometry; [100] hole layer). The surface charge densities, n_s, in units of reciprocal square centimeters, are: 1, 1′, 2, 2′ – 3.1×10^{11}; 4, 4′ – 2.1×10^{12}; 5,5′, 6, 6′ – 3.2×10^{12}. The excitation levels I_p, in units of watts per square centimeter, are: 1, 1′, 4, 4′, 5, 5′ – 4×10^{-2}; 2, 2′, 6, 6′ – 3.

surface. In the region $n_s > n_s^0$, the 2D electrons in the second layer are in the two lower-energy valleys. According to the Ref. 4, the *TO* emission line of the electrons from these valleys in the light propagation direction perpendicular to the surface is unpolarized in a magnetic field. The slight positive polarization observed for the *TO-LO-S* emission line (Fig. 2) results from an orientation of the nondegenerate 2D electrons in the magnetic field, and it is determined by the polarization of the weak *LO* line. Because of the large Fermi energy of the holes in the first layer, the holes do not become oriented in a magnetic field, and they do not contribute to the polarization of the emission. At high excitation levels, the S line is essentially unpolarized because of the large Fermi energy of the electrons. The sign of the polarization of the S_0 line is opposite that of the polarization of the S line (Fig. 2). This result may be evidence that the energy of the orbit-valley splitting of the electron states in the surface excitons is small and that the observed polarization of the *TO-LO-*S_0 line stems from an orientation of electrons in the magnetic field and is determined by the polarization of the *TO* line. As the temperature is raised, the degree of polarization of the S_0 emission line and that of the S emission line decrease. Since the emission line of the surface electron-hole droplets in a magnetic field is essentially unpolarized, the observed degree of polarization peaks at the short-wave edge of the spectrum, in the region of the maximum contribution of the emission from surface excitons. With increasing excitation level, the contribution of the S_0 line to the emission decreases, causing a decrease in the average degree of polarization of the emission. At low excitation levels, the radiative recombination of multiexciton complexes bound to the surface-charge layer may contribute substantially to the *S-EHD* line (Figs. 1 and 2).

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