Two-dimensional electron-hole system on the surface of silicon

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A two-dimensional state of nonequilibrium electron-hole pairs, associated with the [111]-electronic layer of surface charge in silicon is observed. It is established that the two-dimensional electron-hole liquid is not produced in such a system at temperatures $T \geqslant 2$ K.

We have observed previously in silicon MOS structures (metal-oxide-semiconductor) a new state of nonequilibrium electron-hole pairs (*e-h* pairs), associated with the [100]-hole layer of surface charge.[1] In the present work we observed a two-dimensional state of *e-h* pairs, associated with the [111]-electron layer of surface charge in silicon. The investigation of polarization of recombination radiation of *e-h* pairs in a magnetic field under different levels of optical excitation indicates that as a result of repulsion of *e-h* pairs a two-dimensional electron-hole liquid (*S*-EHL) is not formed in such a system at temperatures $T \geqslant 2$ K.

As in Ref. 1 the formation of the two-dimensional state of *e-h* pairs as a result of the binding of excitons with the surface charge is accompanied by the appearance of a new line of recombination radiation (the S line in Fig. 1), whose spectral width and spectral position depend on the voltage U on the structure and, therefore, on the surface charge density $n_s \approx \epsilon(U_0 - U)4\pi ed$, where $\epsilon \simeq 3.9$ is the dielectric constant of

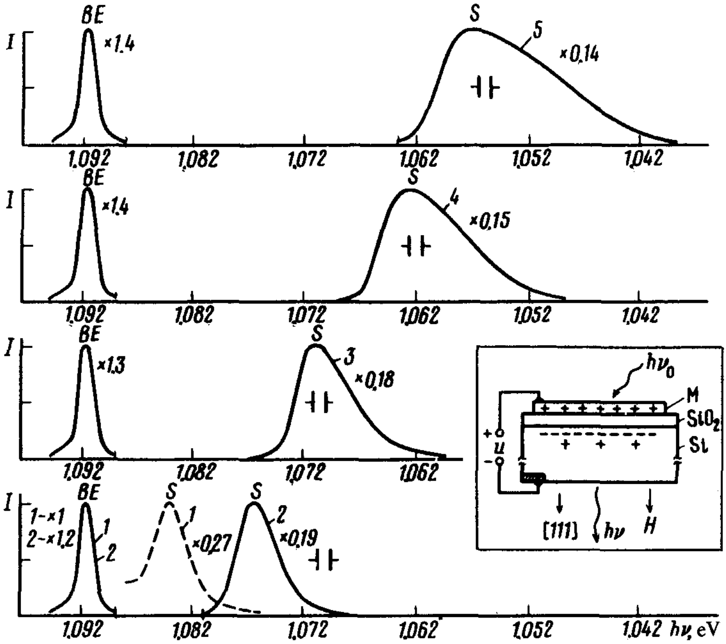

FIG. 1. Spectral distribution of recombination radiation of silicon I at $T = 1.9$ K, TO/LO line. (MOS structure 1 P 111, prepared on a plate of Si:P with donor density $n_D \simeq 2\times10^{15}$ cm^{-3}). The voltage on the structure U ($U<0$): 1) 0, 2) 12.5 V, 3) 25 V, 4) 50 V, 5) 75 V. The level of excitation $I_P \simeq 0.2$ W·cm^{-2}. The magnetic field $H = 0$. The BE-TO is the emission line of the exciton bound to the neutral donor (phosphorus). The inset shows the distribution of the charge in the MOS structure, $h\nu_0$ is the energy of the quantum of excited radiation, $h\nu$ is the energy of the quantum of recombination radiation, and M denotes the metal.

the oxide, U_0 is the threshold voltage,[1] e is the charge of an electron, and d is the thickness of the oxide. The surface density of electrons $n_e = n_s + n_h$ and the surface density of holes n_h at low temperatures in this case are[2]

$$n_e = \frac{\nu_e m_e}{\pi\hbar^2} E_F^e, \qquad n_h = \frac{\nu_h m_h}{\pi\hbar^2} E_F^h . \tag{1}$$

Here E_f and E_f are the Fermi energies of the electrons and holes, which determine collectively the width of the S line along its base. $\nu_e = 2$ and $\nu_h = 1$ are the number of valleys[2] [it is also possible that $\nu_e = 6$ (Ref. 3)]. The effective mass of electrons $m_e \simeq 0.4m_0$,[2] where m_0 is the mass of a free electron. The effective mass of holes at low hole density is $m_h \simeq 0.3m_0$.[2,4] The S line is clearly observed in the region $n_s \approx (0.3$–$7)\times10^{12}$ cm^{-2}, and its width with -10 V $> U > -75$ V depends linearly on U. The existence of the S line with $U = 0$ and small values of U with inverse polarity ($0 < U < 12$ V) indicates the presence of a built-in charge on the oxide-semiconductor interface.

A two-dimensional e-h system forms on the surface of silicon primarily as a result of the attractive forces acting between the electrons and the two-dimensional electronic surface-charge layer. The average distance of electrons in this layer from the silicon surface, which is determined by the wave function of the lower quantum energy level, is $a_e \approx 2\times 10^{-7}$ cm. Since the electrons forming the layer of surface charge are located in a potential well and their density outside the well is small, the attraction of holes to the metallic electronic layer with low hole density at large distances from the surface can be approximately described by the image potential,[5-7] $V_h(z) \sim -e^2/4\epsilon_0 z$, where z is the distance between the hole and the electronic layer, and $\epsilon_0 \simeq 11.4$ is the dielectric constant of silicon. For such a potential, in the adiabatic approximation the radius of the wave function of the hole a_0^h and the binding energy of the lower quantum level E_0 are[6]

$$a_0^h = \frac{4\hbar^2\epsilon_0}{m_{h\perp}e^2}, \qquad E_0 = \frac{1}{32}\,\frac{m_{h\perp}e^4}{\epsilon_0^2\hbar^2}. \tag{2}$$

Here $m_{h\perp} \simeq 0.52 m_0$ is the effective mass of holes along the direction $z\|[111]$. The quantity $a_0^h \approx 5\times 10^{-7}$ cm characterizes the average distance between electrons and holes. For a large density of holes in the region $n_h > (a_0^h)^{-2}$, the attraction of holes to the electron layer is due to the electric field $E = 4\pi e n_h \epsilon_0^{-1}$, which is created by additional electrons with density n_h. The presence of this field must lead to the appearance of an electrostatic shift of the S line in the spectrum toward shorter wavelengths of the order of $\Delta E_{es} \sim (\hbar^2/2m_{h\perp})^{1/3}(eE)^{2/3}$ for $n_h > (a_0^h)^{-2}$. The quantity ΔE_{es} characterizing the energy of the electrostatic repulsion of e-h pairs can prevent the formation of S-EHL.[1] Whether S-EHL is present or missing can be determined by measuring the pair density n_h for different levels of excitation I_P.

To measure n_h we used a method based on the measurement of the degree of circular polarization of the radiation P_N in a magnetic field H in the Faraday geometry.[8] The degree of polarization of the radiation of nondegenerate two-dimensional holes and degenerate two-dimensional electrons with $|\langle s_z\rangle| \ll |\langle j_z\rangle|$, where $\langle s_z\rangle$ and $\langle j_z\rangle$ are the average angular momenta of the electrons and holes,[8-10] is determined by the orientation of heavy holes in a magnetic field and is given by

$$P_N = \sigma_N \tanh\left(3g_1\frac{\mu_0 H}{2kT}\right). \tag{3}$$

Here μ_0 is the Bohr magneton, σ_N is a constant,[9] and $g^* = 3g_1$ is the g-factor of holes. The energy of the state of light holes is much higher[2] and does not contribute to the S line of the radiation. For degenerate holes and degenerate electrons in a weak magnetic field we would have

$$P_N = 2\sigma_N(\langle s_z\rangle - \langle j_z\rangle) = 2\sigma_N\left(3g_1\frac{\mu_0 H}{4E_F^h} - g\frac{\mu_0 H}{4E_F^e}\right), \tag{4}$$

where g is the g-factor of electrons. It is evident from Figs. 2 and 3 that the quantity P_N for the S line with $I_P \lesssim 0.1\ \mathrm{W\cdot cm^{-2}}$ does not depend on I_P and is determined by curve 1 (Fig. 2), which coincides with the theoretical dependence (3) with $\sigma_N = \sigma_{TO/LO} \simeq 0.5$ and $g^* = 3g_1 \simeq 2.5$. The quantity $g^* = 2.5$ that we have found agrees well with the quantity $g^* = 2.4$ obtained in Ref. 4. At $I_P \gtrsim 0.5\ \mathrm{W\cdot cm^{-2}}$, the quantity

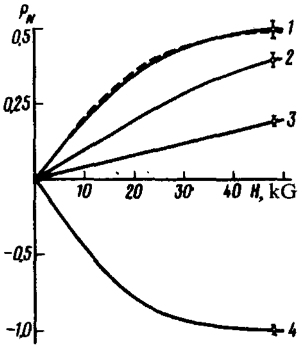

FIG. 2. Dependence of the degree of circular polarization of radiation P_N (1–3) at the peak of the S line on the magnetic field H at a temperature $T = 1.9$ K and voltage on the structure-$U = 25$–75 V. (H‖[111], Faraday geometry, TO/LO line). Excitation level I_P: 1) $\leqslant 0.1$ W · cm^{-2}; 2) 0.7 W · cm^{-2}; 3) 6 W · cm^{-2}. The dashed curve corresponds to the theory for $\langle s_z \rangle = 0$, $T = 1.9$ K, $\sigma_N = 0.5$, $g^* = 3g_1 \simeq 2.5$. Curve 4 shows the degree of polarization of the NP emission line of the exciton bound to the neutral donor.

P_N decreases with increasing I_P, and the S line is displaced in the spectrum toward shorter wavelengths (Figs. 2 and 3). According to (1) and (4), this decrease of P_N is related to the increase in n_h and the displacement of the S line in the spectrum toward shorter wavelengths is due to the electrostatic energy ΔE_{es}, which increases with increasing n_h. The theoretical estimate of the electrostatic shift ΔE_{es}, found from P_N

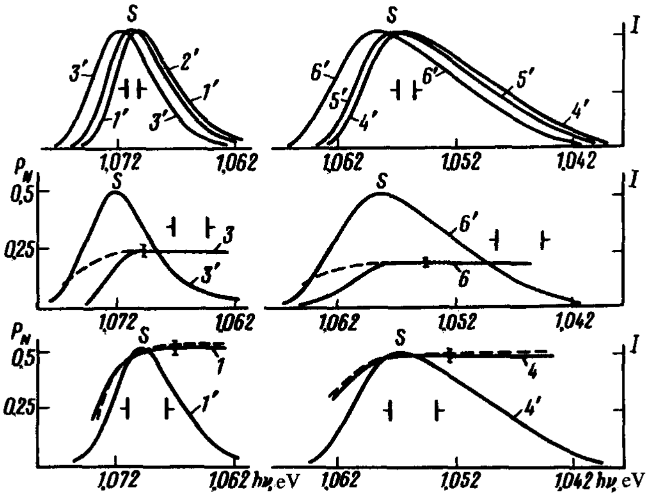

FIG. 3. Spectral distribution of radiation I (1′–6′) and the degree of circular polarization P_N (1,3,4,6) of the S line with $T = 1.9$ K in a magnetic field $H = 50$ kOe (H‖[111], Faraday geometry, TO/LO line). Voltage on the structure — U: 1′,2′,3′,1,3) 25 V; 4′,5′,6′,4,6) 75 V. Excitation level I_P:1′,1,4′,4)$\leqslant$0.1 W · cm^{-2}; 2′,5′) 0.7 W · cm^{-2}; 3′,3,6′,6) 6 W · cm^{-2}. The dashed curve corresponds to the theory[8–10] with $\sigma_{TO} = 0.6$, $\sigma_{LO} \simeq -0.55$, the ratio of the LO and TO line intensities $I_{LO}/I_{TO} \simeq 0.11$ and the energy of the LO-TO splitting $\Delta E_{LO\text{-}TO} \simeq 1.8$ meV.

and n_h, agrees in order of magnitude with the observed value of ΔE_{es}. The results of the investigation of polarization of the S line of radiation in a magnetic field indicates that the density of pairs n_h depends on the level of excitation and in the region $IP \lesssim 0.1$ W · cm^{-2} the S line is due to recombination of degenerate two-dimensional electrons and nondegenerate two-dimensional holes with density $n_h < 3 \times 10^{10}$ cm^{-2}. Therefore, the S-EHL in the two-dimensional system that we studied is not formed at $T \geqslant 2$ K.

The dashed line in Fig. 3 shows the theoretical degree of polarization of the S line, calculated by taking into account *TO-LO* splitting.[8–10] It is evident that at $I_P >$ W · cm^{-2} the observed magnitude of P_N at the short-wavelength edge of the line is much smaller than the theoretical value. This disagreement is caused by the fact that the nonequilibrium electrons near the Fermi level are oriented in a magnetic field and, according to (4), decrease P_N by an anomalously large amount, $2\sigma_N \langle s_z \rangle$. The amplification factor for the spin susceptibility of electrons in this case reaches the value $\langle s_z \rangle / \langle s_z \rangle_P = 2.5$, where $\langle s_z \rangle_P = -g\mu_0 H / 4E_F^e$, $g \simeq 2.6$.[2] This phenomenon is apparently analogous to the amplification of the spin susceptibility of holes in strongly doped Si:B observed by Altukhov *et al.*[10] It has also not been ruled out that the observed effect could be related to the absence of spin equilibrium in the electronic layer.

The electrostatic repulsion between *e-h* pairs, which facilitates spreading of *e-h* pairs along the silicon surface, is the main reason for the absence of the S-EHL associated with the surface charge layer. At the same time the two-dimensional *e-h* system, which is similar to the one investigated in this work, is under certain conditions a useful object for experimental study of a number of interesting phenomena examined theoretically in Refs. 11–13.

[1]P. D. Altukhov, A. V. Ivanov, Yu. N. Lomasov, and A. A. Rogachev, Pis'ma Zh. Eksp. Teor. Fiz. **38**, 5 (1983) [JETP Lett. **38**, 4 (1983)].
[2]G. Landwehr, Festkorperproblem **XV**, 49 (1975).
[3]D. C. Tsui and G. Kaminsky, Phys. Rev. Lett. **42**, 595 (1979).
[4]K. von Klitzing, G. Landwehr, and G. Dorda, Solid State Commun. **15**, 489 (1974).
[5]Yu. F. Lozovik and V. N. Nishanov, Fiz. Tverd. Tela **18**, 3267 (1976) [Sov. Phys. Solid State **18**, 1905 (1976)].
[6]M. W. Cole and M. H. Cohen, Phys. Rev. Lett. **23**, 1238 (1969).
[7]V. G. Litovchenko, Surf. Sci. **73**, 446 (1978).
[8]P. D. Altukhov and A. A. Rogachev, Fiz. Tverd. Tela **23**, 1956 (1981) [Sov. Phys. Solid State **23**, 1142 (1981)].
[9]P. D. Altukhov, K. N. El'tsov, and A. A. Rogachev, Fiz. Tverd. Tela **23**, 552 (1981) [Sov. Phys. Solid State **23**, 310 (1981)].
[10]P. D. Altukhov, K. N. El'tsov, and A. A. Rogachev, Pis'ma Zh. Eksp. Teor. Fiz. **31**, 221 (1980) [JETP Lett. **31**, 202 (1980)].
[11]Yu. E. Lozovik and V. I. Yudson, Pis'ma Zh. Eksp. Teor. Fiz. **22**, 117 (1977) [JETP Lett. **22**, 53 (1977)].
[12]Y. E. Lozovik and V. D. Yudson, Solid State Commun. **22**, 117 (1977).
[13]Yu. A. Bychkov and E. I. Rashba, Zh. Eksp. Teor. Fiz. **85**, 1826 (1983) [Sov. Phys. JETP, to be published].

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