Recombination radiation of nonequilibrium electron-hole pairs associated with a surface charge layer in silicon

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A new recombination radiation line, due to electron-hole pairs associated with a surface charge layer, arises in MOS (metal–oxide–semiconductor) structures in silicon in the presence of an electric field. The possibility for the existence of a two-dimensional electron-hole liquid in such a system is examined.

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We have discovered a new recombination radiation line (*S*-line, Fig. 1) arising in MOS structures in silicon with optical excitation in the presence of an external electric field. The intensity, spectral position, and spectral width of the *S*-line depend on the magnitude and sign of the voltage *U* on the structure (Figs. 1 and 2). In the experiments, we used MOS structures prepared on the [100] surface of *n*- and *p*-type silicon. The recombination radiation was excited by a continuous argon laser through a semi-

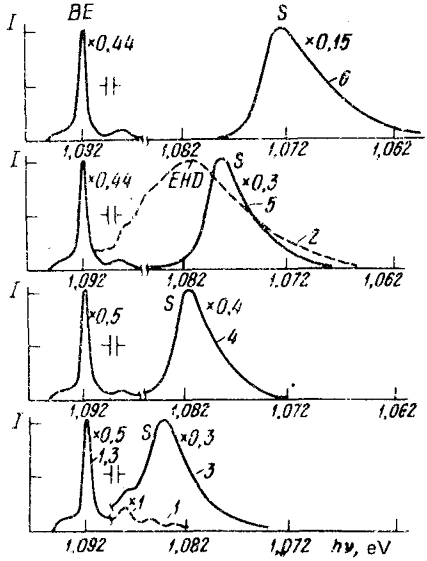

FIG. 1. Spectral distribution of recombination radiation of silicon *I* at $T = 1.9$ K, *TO/LO* lines. (MOS structure, No. 3R2 with orientation [100], prepared on a Si:P plate with donor density $n_D \cong 3 \times 10^{14}$ cm^{-3}). The voltage *U* on the structure is: 1, 2 — 0; 3 — 13.8 V; 4 — 21.6 V; 5 — 29.3 V; 6 — 44.75 V. The level of excitation I_P is 1, 3, 4, 5, and 6 — 1 W cm^{-2}; 2 — 5×10^2 W cm^{-2}. *BE* is the *TO* emission line of exciton bound to a neutral donor (phosphorus); EHD is the *TO/LO* emission line of three-dimensional EHD at $U = 0$; curve 1 indicates bound multiexciton complexes with $U = 0$.

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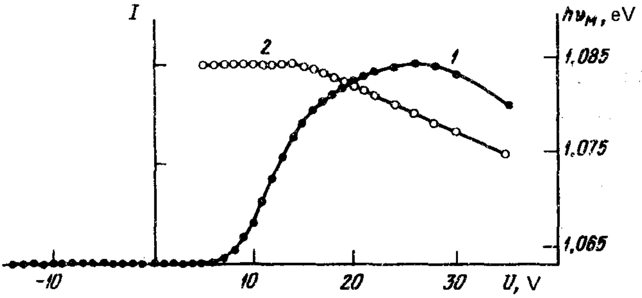

FIG. 2. Peak intensity of the S-line I (1) and spectral position of the peak of the S-line $h\nu_m$ (2) as a function of the voltage U on the structure at $T = 1.9$ K and excitation level $I \approx 1$ W cm^{-2} (MOS-structure No. 3R2).

transparent metallic coating. After passing through the opposite face of silicon along the [100] direction the radiation was recorded with the help of the setup described in Ref. 1. The experimental data for n-Si and p-Si turned out to be very similar. In both cases, the S-line arises only with the appearance of a p channel in the surface conductivity. The threshold voltage at which the S-line appears (Fig. 2) is close to the threshold voltage U_0, characteristic of the appearance of conductivity in the p-channel at low temperatures.

Our experimental results permit interpreting the S-line as in emission line of electron-hole pairs (e–h pairs) associated with the surface charge layer. Let us examine the mechanism responsible for the formation of such a system. The interaction of excitons, generated in the crystal, with the surface charge layer causes the excitons to be attracted to the surface, their association with the layer, and formation of a two-dimensional electron-hole system with a surface electron density n_e and surface hole density $n_h = n_s + n_e$, where $n_s \cong \epsilon(U - U_0)/4\pi ed$, $\epsilon \cong 3.9$ is the dielectric constant of the oxide, e is the electron charge, and d is the thickness of the oxide. In the presence of the external field and interaction forces between charges, potential wells form for electrons and holes near the surface (Fig. 3). These wells lead to quantization of the motion of electrons and holes perpendicular to the surface.[2] In addition, all electrons and holes are located in the lower quantum levels, while their motion along the surface is free. The Fermi energy of electrons and holes E_F^e and E_F^h in this case are (Ref. 2)

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

where $\nu_e = 2$ and $\nu_h = 1$ are the number of valleys.[2] The effective mass of electrons $m_e \cong 0.2m_0$,[3] where m_0 is the free electron mass. The effective mass of holes in (1) can be determined by the empirical relation $m_h \approx (n_h/n_0)^{1/2} m_0$, where $n_0 \cong 3 \times 10^{12}$ cm^{-2}, which includes the increase in m_h with increasing n_s in the region $n_s \cong (1\text{–}3) \times 10^{12}$ cm^{-2}, as observed in Ref. 4.

The width of the S-line at the base of the spectrum is $(E_F^e + E_F^h)$. Comparison of the width of the S-line with the Fermi energy of holes for the surface charge layer in the absence of optical excitation shows that the observed quantities E_F^e and n_e in the region of values $n_s \approx (1\text{–}6) \times 10^{12}$ cm^{-2} for which the S-line exists are not large: $E_F^e < 3$

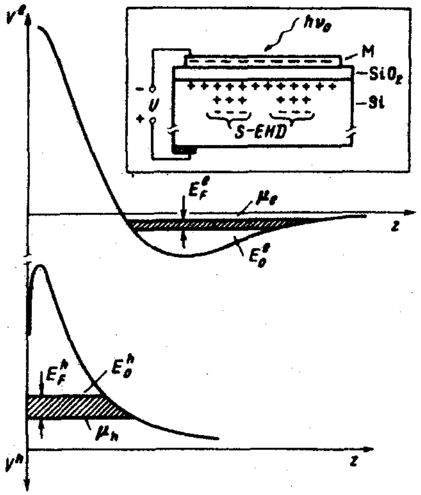

FIG. 3. Voltage distribution for electrons V^e and holes V^h along the z direction, perpendicular to the silicon surface (qualitative appearance). E_0^e and E_0^h are the lower quantum levels of electrons and holes; μ_e and μ_h are the chemical potentials of electrons and holes; E_F^e and E_F^h are the Fermi energies of electrons and holes. The insert shows a diagram of the MOS structure and the distribution of electron and hole charges in S-EHD. $h\nu_0$ is the energy of the exciting radiation, M is the metal, SiO_2 is the oxide.

meV, and $n_e \lesssim 5\times 10^{11}$ cm^{-2}. The shape of the S-line can depend strongly on fluctuations of the surface potential and the dispersion law for holes. It should be noted that the shape of the S-line and its spectral position are nearly independent of the excitation level I_P for $I_P < 1$ W cm^{-2}. In this case, the existence of the S-line was observed clearly up to $I_P \sim 10^{-3}$ W cm^{-2}. Measurements of the degree of circular polarization of the S-line of P_N in a magnetic field $H \| [100]$ in the Faraday geometry at temperature $T = 1.9$ K showed that the S-line is virtually unpolarized ($P_N < 3\times 10^{-2}$ for the S-line with $H \leqslant 50$ kOe and $P_N \cong 0.65$ for the BE line for $H = 50$ kOe). This result can be observed when the Fermi energy E_F^e greatly exceeds the paramagnetic splitting of electrons or when the spin relaxation time of electrons is much longer than their lifetime. As the temperature is increased, the S-line is displaced toward short wavelengths, its intensity drops, and for $T > T_0$ (where T_0 is the threshold temperature which does not depend on I_P) the S-line is not observed. For structure No. 3R2 (Fig. 1), $T_0 \cong 21$ K for $U \leqslant 22$ V. Then, as U increases, T_0 increases up to $T_0 \cong 35$ K for $U \cong 45$ V. The observed temperature dependence of the S-line indicates that in the region $T \sim T_0$, the evaporation of excitons from the surface into the bulk increases, and the $T > T_0$ the state of e–h pairs associated with the surface charge layer does not form.

The chemical potential of e–h pairs, which determines the position of the short-wavelength edge of the S-line at low temperatures, is (Fig. 3)

$$\mu = \mu(n_s + n_e, n_e) = (E_0^h + E_F^h) + (E_0^e + E_F^e), \tag{2}$$

where E_0^h and E_0^e are the energies of the lower quantum levels of holes and electrons relative to the bottom of the corresponding bands. For $n_e \ll n_s$, the main contribution to μ is determined by $\mu_h = E_0^h + E_F^h$. Estimates performed with the help of Refs. 5 and 6 show that in the region $n_s \cong (1\text{–}6)\times 10^{12}$ cm^{-2}, $|\mu_h|$ increases with increasing n_s, giving rise to the observed displacement of the S-line in the spectrum toward longer wavelengths with increasing voltage U. In this case, the value of n_s, corresponding to the threshold for the appearance of the S-line, is determined from the condition $\mu_0 + E_{\text{ex}} = 0$, where $E_{\text{ex}} \cong 14.7$ meV is the binding energy of the three-dimensional exciton, and $\mu_0 = \mu(n_s, 0)$ is the chemical potential of e–h pairs for $n_e = 0$. The absence of an S-line with formation of the n channel of surface conductivity ($U < 0$ in Fig. 2) is apparently explained by the fact that for the n-channel $\mu_0 + E_{\text{ex}} > 0$ due to the large kinetic energy of electrons.

It is possible that in the two-dimensional system examined above, nonequilibrium e–h pairs exist at sufficiently low temperature in the form of a two-dimensional electron-hole liquid (S-EHL) and form two-dimensional electron-hole drops (S-EHD), shown schematically in Fig. 3, with surface electron density $n_e = n_{e0}$ and surface hole density $n_h = n_s + n_{e0}$. In this case, the electron density outside S-EHD at low temperatures is much lower than n_{e0}. Exchange-correlation interaction can facilitate the formation of S-EHL. The kinetic energy of electrons and holes, as well as the electrostatic energy, arising due to the fact that electron and hole charges in the presence of an external field are located at a different distances from the surface of the semiconductor (Fig. 3), could inhibit the formation of S-EHL. The properties of S-EHL to a certain extent must be close to the properties of a two-dimensional EHL, examined theoretically in Refs. 7–9, and to the properties of a two-dimensional EHL associated with the surface of the semiconductor and arising with different methods of working the surface.[10,11] Nevertheless, our data do not exclude the possibilities that S-EHL does not form, the S-line corresponds to emission by a two-dimensional e–h plasma, and the quantity n_e is small and can depend on the level of excitation.

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