Radiative recombination of 2*D* electrons with photoexcited holes in silicon metal-insulator-semiconductor structures

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A radiative recombination of 2*D* electrons with photoexcited holes has been observed in silicon metal-insulator-semiconductor structures. The results of spectroscopic measurements agree with the results of simultaneous magnetotransport measurements and reveal the energy dependence of the state density of 2*D* electrons and their Fermi energy.

We have studied metal-insulator-semiconductor (MIS) structures fabricated on the (100) surface of *p*-type silicon with a boron concentration of 10^{15} cm^{-3}. The thickness of the oxide layer in structure No. 1 was 4200 Å, and that in structure No. 2 was 2000 Å. In a metal gate with an area of 8 mm^2 there were a semitransparent part made from an alloy similar to Nichrome and two opaque aluminum parts, which were used to make the ohmic contacts. The structures did not contain contacts to the 2*D* layer (a drain and source); illumination was required to produce an electron inversion channel. We simultaneously carried out spectroscopic measurements and a study of the magnetotransport properties of the electron or hole channels that arose, so that we were able to reliably establish their two-dimensionality and to determine the mobility and density of the 2*D* charge carriers. The conductivity measurements were taken by a contactless capacitive method.[1,2] Both the magnetotransport and spectroscopic measurements were carried out at $T = 1.7$ K.

Figure 1a shows the conductivity σ_{xx} versus the gate voltage (V_g) during the production of an electron inversion layer ($V_g > 0$) and also during the production of a hole accumulation channel ($V_g < 0$) on structure No. 1 in the absence of a magnetic field ($H = 0$) and also at $H = 9$ T (H was perpendicular to the plane of the 2*D* carriers). The two-dimensionality of the electrons in the inversion channel follows unambiguously from the periodicity of the observed Shubnikov oscillations along the V_g scale. From the oscillation period and the behavior $\sigma_{xx}(V_g)$ at $H = 0$ we find the electron and hole mobilities [for structure No. 1, the maximum mobilities at $T = 1.7$ K were

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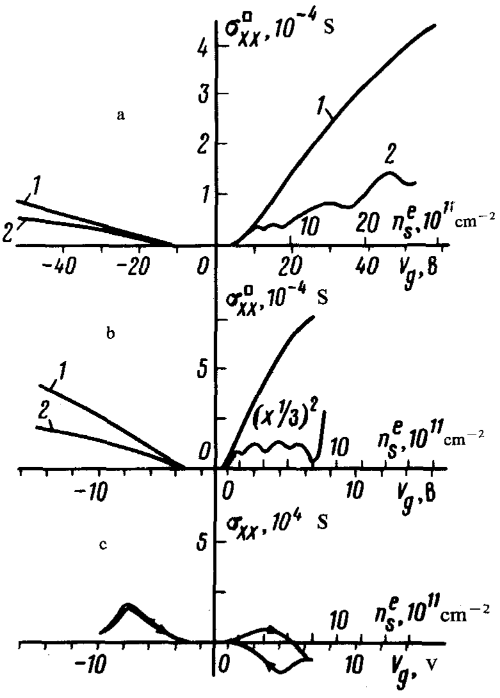

FIG. 1. The mobility σ_{xx} versus the gate voltage V_g and the density n_s^e at $H = 0$ (curve 1) and in various nonzero magnetic fields H (curve 2). a—Metal-insulator-semiconductor structure No. 1, $H = 9$ T; b—MIS structure No. 2, $H = 7$ T; c—"punctured" MIS structure No. 2, with charge leakage through the insulator.

$\mu_e^{\max} = 1.2 \times 10^3$ cm^2/(V·s) and $\mu_h^{\max} = 300$ cm^2/(V·s)], the threshold voltage (V_T) at which the inversion channel begins to form, and the coefficient of the proportionality between the density of 2*D* electrons and the difference $V_g - V_T$ (Fig. 1). An important point is that with increasing intensity (W) of the excitation by the argon laser there is a shift of the pattern of Shubnikov oscillations along the V_g scale (i.e., there is a decrease in V_T). Beyond an intensity $W \geqslant 10^{-3}$ W/cm^2, there are essentially no further changes in the behavior $\sigma_{xx}(V_g)$.

Figure 1b shows the results on $\sigma_{xx}(V_g)$ obtained for structure No. 2 at $H = 0$ and $H = 7$ T. The mobility in this structure was considerably higher than that in structure No. 1, for both electrons and holes: $\mu_e^{\max} = 18\,000$ cm^2/(V·s) and $\mu_h^{\max} = 2000$ cm^2/(V·s), so that the structure of a Landau level (two spin sublevels and two valley-orbital sublevels[3]) could be resolved in the pattern of Shubnikov oscillations. Figure 1c illustrates the observed behavior $\sigma_{xx}(V_g)$ in structure No. 2 after breakdown in the oxide layer, when the resistance of this layer has changed from its original value $\sim 10^{12}\,\Omega$ to $\sim 10^9\,\Omega$. We see that at the SiO$_2$ resistance $\sim 10^9\,\Omega$ there is a rapid leakage of charge carriers, with the result that no electron channel forms at all, while the hole channel disappears as V_g is increased.

To study the recombination radiation of the 2*D* charge layers with photoexcited carriers, we placed the MIS structures in an optical cryostat without a solenoid, but we

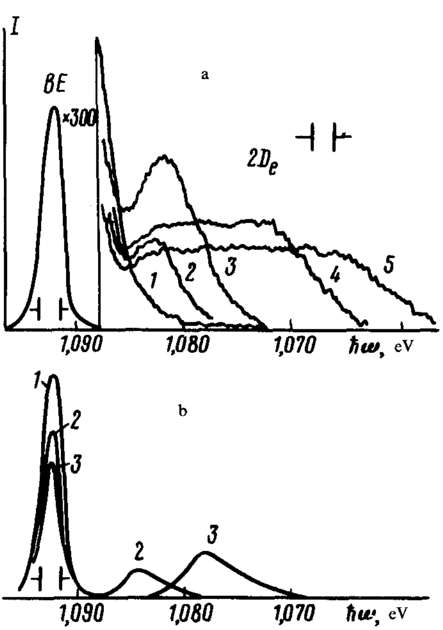

FIG. 2. Emission spectra obtained from MIS structure No. 1 (a) and from "punctured" structure No. 2 (b) for various values of V_g (volts) and n_s^e (units of 10^{11} cm^{-2}): a:1—$V_g = V_T = 0$, $n_s = 0$; 2—$V_g = 4$, $n_s = 2.1$; 3—$V_g = 10$, $n_s = 5.3$; 4—$V_g = 30$, $n_s = 16$; 5—$V_g = 45$, $n_s = 24$. b: 1—$V_g = V_T = -1$; 1—$V_g = 15$; 3—$V_g = 30$.

monitored the dependence $\sigma_{xx}(V_g)$ at $H = 0$ at all times. The emission was detected with a cold photomultiplier operated in the photon-counting regime. The spectral measurements were carried out with a double monochromator with a dispersion of 10 Å/mm.

At gate voltages $V_g \leqslant V_T$, which no electron channel forms, the luminescence spectrum contains only the volume emission of excitons bound to boron (line *BE* in Fig. 2). When a positive voltage which gives rise to a layer of 2*D* electrons is applied to the gate, a new emission line appears in the luminescence spectrum, precisely at $V_g > V_T$; the intensity of this new line is lower than that of line *BE* by a factor of almost 1000 (Fig. 2a). A result different from ours was obtained by Altukhov *et al.*,[4] who reported observing far more intense emission in a Si (100) MIS structure, and then only when a negative voltage was applied to the gate. They proposed a recombination mechanism according to which an electron-hole double layer forms near the surface of the semiconductor. This hypothesis can easily be tested by looking at the results of the magnetotransport measurements. In addition to the charges in the 2*D* layer, there are some additional charges in the interior of the semiconductor, with a surface density n_x, so that electrical neutrality is preserved: $n_M - n_s \pm n_x = 0$, where n_s and n_M are the charge densities in the 2*D* layer and in the gate, respectively. In the absence of an illumination, the density n_x would correspond to the density of negative charges in the depletion region: $n_x = (2\epsilon_0\epsilon_{\rm Si}E_gN_A/e^2) = 11.3\times10^{10}$ cm^{-2} (ϵ_0 is the permittivity of free space, $\epsilon_{\rm Si}$ is the dielectric constant of silicon, E_g is the Si band gap, and N_A is the

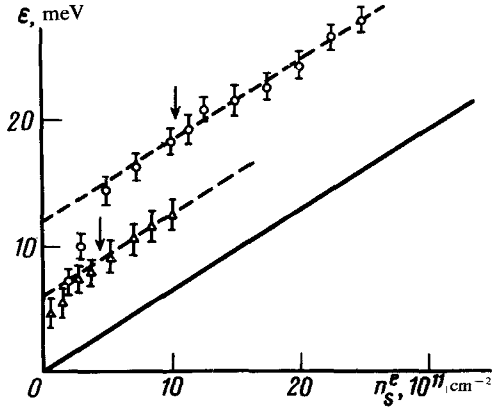

FIG. 3. The Fermi energy (ϵ_F) of the $2D$ electrons versus their density $n_s^e \propto (V_g - V_T)$, as determined from the width of the $2D_e$ line of MIS structures No. 1 (○) and No. 2 (△). The straight line is the theoretical functional dependence $\epsilon_F(n_s)$. The arrows show the density threshold in the mobility determined from the temperature dependence of the conductivity.

impurity concentration[3]). Illumination causes a change in V_T, as we have already mentioned, and from this change we can easily determine the increase in the density of $2D$ electrons. Using the expressions written above, we find $n_x = +(3 \pm 0.5) \times 10^{10}$ cm^{-2} for our case. This result means that there is an electron-hole double layer with a maximum hole surface density $n_h = (3 \pm 0.5) \times 10^{10}$ cm^{-2}. The questions of the two-dimensionality of the second hole layer and of its distance from the surface of the semiconductor remain open, but at such a low density and at the low temperatures the $2D$ holes would presumably be localized.

According to these arguments, the shape of the $2D_e$ emission line should reflect the state density of $2D$ electrons (g_e) broadened by the temperature, the energy distribution of the holes, and the slit width of the spectral instrument. The agreement between the shape of the $2D_e$ line and the function $g_e(\epsilon)$ can be seen directly from Fig. 2a. The deviation from a constant value at the low-frequency edge of the $2D_e$ line is caused by the localization of $2D$ electrons, which give rise to a state-density tail.[3] With increasing V_g, there are increases in n_s and in the Fermi energy ϵ_F of the electrons, as can be seen from the broadening of the $2D_e$ line, but its total intensity remains essentially the same.

Figure 3 shows the width of the $2D_e$ line or the Fermi energy of the $2D$ electrons versus the density according to the results on structures Nos. 1 and 2. In addition to the good agreement between the slopes of the experimental and theoretical curves of $\epsilon_F(n_s)$, we see from Fig. 3 that the width of the tail in the state density of $2D$ electrons found by extrapolating $\epsilon_F(n_s)$ to $n_s \to 0$ is considerably greater for structure No. 1, in which the electron mobility is low.

A study of the $2D$ channels of the holes (at $V_g < 0$) revealed that the intensity of the $2D_h$ line in this case is at least an order of magnitude lower than that of the $2D_e$ line. We also find that in "punctured" MIS structure No. 2, with a SiO_2 layer having a resistance $\sim 10^9$ Ω, the disappearance of the hole channel (Fig. 2b) is accompanied by the simultaneous appearance in the luminescence spectrum of an intense emission line, with an intensity comparable to that of line *BE* and almost three orders of magnitude greater than that of the line $2D_e$ (Fig. 2b). This line is unrelated to the $2D$ charge layers. We do not rule out the possibility that this line is observed in the emission spectra of silicon MIS structures in Refs. 4 and 5.

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