Strong positive magnetoresistance of the electronic inversion layer in the region of the activation conductivity

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A positive exponential magnetoresistance of the electronic inversion layer has been detected on the surface of silicon in the region of activation conductivity. The resistivity increases by an order of magnitude (at temperatures in the range 1.2–4.2 K) in a 70-kOe field.

If the surface density of carriers, n_S, is lower than a certain threshold value, n_{thresh}, known as the mobility threshold, and if the temperature is not too low, the resistivity ρ of the electronic inversion layer increases exponentially at the surface of silicon as the temperature is lowered. The conductivity is linked in this case with the thermal activation of electrons to higher-lying energy levels. For this reason, the density region $n_S < n_{\text{thresh}}$ is generally called the activation conductivity region. The dependence of ρ on the magnetic field H perpendicular to the plane of the layer has been studied extensively at $n_S \lesssim n_{\text{thresh}}$. The value of ρ varied within only 10% in magnetic fields up to $H \sim 100$ kOe and was either positive[1] or negative,[2] depending on the prevailing conditions. The electronic layers were studied experimentally in the MOS structures with a maximum carrier mobility, $\mu_{\max} \lesssim 1.5 \times 10^4$ cm^2/(V·s). Technological progress in the fabrication of MOS structures has now made available for physical testing samples with 2–3 times greater mobilities.[3] The experiments described below have shown that at $n_S \lesssim n_{\text{thresh}}$ the $\rho(H)$ dependence is much stronger in such samples.

The experiments were carried out with MOS structures on the (001) surface of a p-type silicon with a resistivity of 20 Ω·cm at room temperature. The channel was 5×0.8 mm in size, $\mu_{\max} = 3.5 \times 10^4$ cm^2/(V·s) at $T = 1.2$ K, and the capacitance was $C = 700$ pf. The resistivity was determined from the decrease in the voltage between the potential contacts on one side of the channel and from the measurements of the time constant τ of the charge of the MOS structure. The current I between the source and the drain in the first case was chosen from the condition

$$RI \ll V_g \,, \tag{1}$$

where R is the resistance between the source and the drain, and V_g is the starting voltage. By using this relation we obtain a uniform electron density in the channel and we can ignore the dependence $n_S(I)$. In the case of the samples tested by us we have $R = 6.25\rho$. To satisfy condition (1) within $\rho \approx 10^6$ Ω/□, we used $I = 10$ nA. To improve the signal-to-noise ratio at such small currents, we used 63-Hz alternating current in our measurements. From the measurements of ρ without a magnetic field we found that $n_{\text{thresh}} = 1.5 \times 10^{11}$ cm^{-2}. At this density we have $\rho = 3 \times 10^4$ Ω/□.

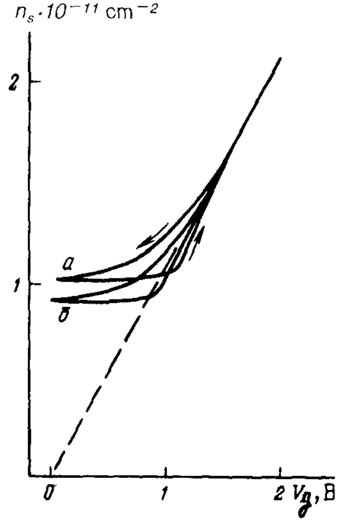

FIG. 1. Carrier density n_S in the channel versus the gate voltage V_g at $H = 70$ kOe (a) and at $H = 0$ (b).

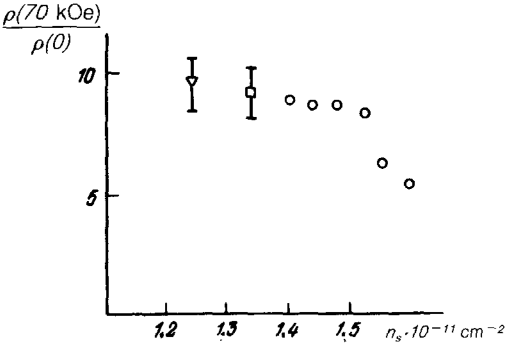

FIG. 2. Relative magnetoresistance versus n_S. Notation: ○—Data obtained from measurements of the voltage drop at a current of 10 nA, a frequency of 63 Hz, and $T = 4.2$ K; ▽—measurements of τ at $T = 4.2$ K; □—the same at $T = 1.2$ K.

The value of ρ increases exponentially as n_S is decreased, increasing (at $T = 4.2$ K) by a factor of 30 as n_S is decreased by 10^{10} cm^{-2}. This functional dependence becomes even steeper as the temperature is lowered. Such a rapid increase in the resistance limits the density region in which ρ can be measured by the method described above to $n_S \gtrsim 1.4 \times 10^{11}$ cm^{-2}. At lower densities $n_S = 1.2$–1.3×10^{11} cm^{-2} the effect of H on ρ can be determined from the change in the time constant, $\tau \propto C\rho$, of the charge of the channel-gate capacitance C at $I = 0$ in a magnetic field. The time constant τ can be determined from the deviation of the charge $Q = en_S S$ of the MOS structure from the equilibrium value $Q = CV_g$ due to the change in V_g (S is the surface area of the channel). In this case Q must be measured independently of V_g. We have determined here the change in Q due to the change in V_g as a time integral of the charge current of the gate in the MOS structure, by analogy with the manner in which this procedure was carried out in Ref. 4. We found that V_g varies at the rate of 0.1 V/s over the range 0–3 V. The functional dependences $n_S (V_g) = Q(V_g)/(Se)$ determined in this manner are shown in Fig. 1. If the absolute value of n_S is known in the region studied, it can be determined at $V_g > 2$ from the Shubnikov–de Haas effect. In the region of small values of V_g we can estimate ρ from the hysteresis, which is

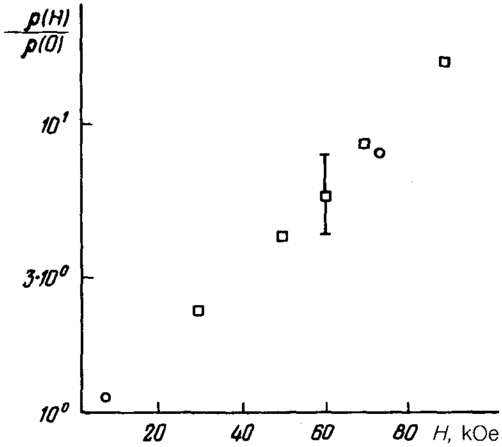

FIG. 3. Relative magnetoresistance versus the magnetic field H. The notation is the same as in Fig. 2.

governed by the time constant τ, at least in the region in which n_S differs moderately from the equilibrium value for the given V_g and in which the change in the charge distribution in the channel may be assumed small. The resistivity in this case is estimated to be $\sim 10^8\ \Omega/\Box$.

Figure 2 is a plot of the ratio $\rho(70\text{ kOe})/\rho(0)$ versus n_S. In the range $1.2\times 10^{11}\text{ cm}^{-2} < n_S \lesssim 1.5\times 10^{11}\text{ cm}^{-2}$, this ratio remains roughly constant and is independent of the temperature. The dependence $\rho(H)$ is exponential in nature (Fig. 3). At $V_g = 0$, some residual charge density n_0 remains in the channel (Fig. 1), which does not decrease to any appreciable extent over a time measured in several tens of minutes. We thus see that in this region we have $\rho \gtrsim 10^{12}\ \Omega/\Box$. Since n_0 depends on H, we can conclude that the observed effect occurs even at these large values of ρ.

The most probable cause of the exponential dependence of ρ on H, in our view, is the mechanism which in similar to the mechanism of an enormous positive magnetoresistance in doped semiconductors.[5,6] This means that at carrier densities $n_S \lesssim 1.5\times 10^{11}\text{ cm}^{-2}$ the conductivity is of a hopping nature and that the magnetic field changes the probability of the hopping conductivity, reducing the extent of the overlap of the wave functions of the electrons. A further study of the described effect may in this case yield information on the nature of the localizing potential, the spacing between the localization centers, etc. The Wigner crystallization in a magnetic field should not, however, be ruled out as a possible cause of the increase in the number of localized carriers. We know that a magnetic field can increase the existence domain of a crystal, shifting the boundary of cold melting in the direction of larger[7] n_S, which could in the final analysis lead to effects similar to those described above.

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