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On the Influence of Ionic Polarization of Transistor Si-Structures on the Conductivity of *p*-Type Channels

E. I. Goldman[a], **V. G. Naryshkina**[a], **and G. V. Chucheva**[a, *]

[a]*Fryazino Branch, Kotelnikov Institute of Radio Engineering and Electronics, Russian Academy of Sciences,*
Fryazino, Moscow oblast, 141190 Russia

**e-mail: gvc@ms.ire.rssi.ru*

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Abstract—In the range of transverse magnetic field induction values of 0–4.5 T at temperatures of 100–200 K, the conductivity of the inversion channel of transistor Si-structures is measured after ion polarization and depolarization of samples. It was found that during polarization at a temperature of 420 K under the action of a strong electric field, around 6.5×10^{11} cm^{-2} ions flowed in the oxide. It was found that, up to the channel opening threshold, conductivity in the source–drain circuit is achieved due to thermal activation of charge carriers to the leakage level in the unordered potential created by the chaotic distribution of ions along the semiconductor surface. It is shown that after opening of the channel (intersection of the Fermi level of holes on the semiconductor surface with the flow level in the chaotic potential), ions appear in the conductivity as additional scattering centers; therefore, in a polarized state, the effective channel mobility is less than in the depolarized one.

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Modification of the electronic properties of the interfaces in metal–insulator–semiconductor structures after ionic polarization of the insulating layer is a well-known feature of silicon planar transistors. As a result of polarization, biases occur in the threshold voltages in the opening of inversion channels due to accumulation of the built-in charge [1], as well as changes in the band structure of the conducting paths due to the resulting high concentration of localized impurity states in the semiconductor–dielectric interface [2, 3]. Planar nonuniform polarization makes it possible to create a regular localized charge distribution with a two-dimensional potential relief, forming various quantum-size nanoscale regions near the semiconductor surface [4, 5]. It was found [6, 7] that the ionic polarization of metal–oxide–semiconductor (MOS) transistor structures leads to an increase in the effective electron mobility in the inversion channel of Si–SiO$_2$ interfaces. This phenomenon for *n*-type channels was explained by the formation of a new electrical transfer path along the surface impurity zone related to delocalized D^- states generated by neutralized ions in the insulating layer of the interface with a semiconductor [8]. Since positively charged ions cannot form bound states with holes, polarization of the oxide in contact with the *p*-type inversion channel should yield a different, as compared to [8], pattern of changes in the conductive properties. The aim of this work is to experimentally investigate this question.

Experiments were performed similarly to studies [8] using a computerized setup [9] on Si–MOS transistors with an inversion hole channel, a thermal gate oxide thickness h = 1000 Å, source–drain electrode width W = 1 mm, and distance between them of L = 10 μm. The objects were formed using standard silicon technology. The current–voltage characteristics were measured on sawtooth pulses from an Agilent 3322A generator with a field sweep rate of $\beta = 0.32$ V/s with a gate voltage amplitude $|V_g| = 10$ V and constant bias on the drain of $V_d = -0.01$ V. As in [8], the polarization and depolarization of the oxide were carried out at voltages of $V_g = 10$ and -10 V on the field electrode, respectively, and in the drain $V_d = -0.01$ V for 1 h at 420 K.

After field and temperature effects, the sample was placed in a cryomagnetic liquid-free system, allowing current and voltage measurements in the temperature range from 6 to 300 K and in magnetic fields of up to 8 T [10]. To avoid ion drift in strong electric fields, the conductivity of the inversion channel was measured at temperatures no higher than 200 K; at the same time, their values were controlled by a Lakeshore 335 thermostat with an accuracy of 0.01 deg.

Figure 1 shows the dependences of the currents in the inversion channel I_d on the gate voltage V_g after polarization and depolarization at different temperatures. As in previous studies [6–8], the effective mobility of free charge carriers was used to monitor

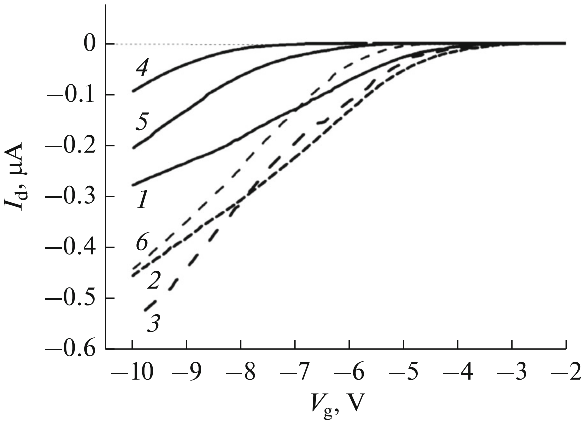

Fig. 1. Current dependence I_d in inversion channel of Si–MOS transistor on potential of gate V_g after depolarization (curves *1–3*) and polarization (curves *4–6*) at different temperatures: 200 K (*1*, *4*), 150 K (*2*, *5*), 100 K (*3*, *6*); drain voltage $V_d = -0.01$ V.

the influence of all effects on the conductivity of the inversion channel:

$$\mu = \left(1/C_i\right) d\sigma/dV_g, \qquad (1)$$

which is determined in the quasilinear area of the corresponding characteristic $I_d\left(V_g\right)$ (see Fig. 1), where $\sigma = \left(I_d L/W\left|V_d\right|\right)$ is the ohmic channel conductivity, I_d is the current in the source–drain circuit, and C_i is the capacity of the gate insulating silicon oxide layer.

In contrast to *n*-type transistor channel, under our conditions after the polarization current I_d modulo for the same field strength, values V_g were dramatically (by several times) less than after depolarization; the magnitude μ does not increase, but on the contrary, significantly decreases (see below). The transition from the depolarized to the polarized state substantially biases the channel opening threshold. This domain of currents I_d is shown in Fig. 2. The threshold voltage bias decreases with decreasing temperature from 3 V at 200 K to 1.5 V at 100 K. These figures correspond to the increase in concentration of positive intrinsic charge at the Si–SiO$_2$ interface after polarization from the depolarized state at 6.5 × 10^{11} cm^{-2} (200 K) and 3.2 × 10^{11} cm^{-2} (100 K). Apparently, such a significant difference in the concentration values localized at the Si–SiO$_2$ interface of charges is due to the nonstationarity of the opening of the channel at low temperatures: initially for $V_g \approx 0$, the ions are sufficiently neutralized [11–13] and the recombination of electrons trapped on them, at least in areas of bunches of impurity particles, is delayed with respect to the sweep of the field strength $dV_g/dt = -0.32$ V/s. This assumption also corresponds to a significantly wider part of the nonlinear dependence $I_d\left(V_g\right)$ in the polarized state after opening of the channel at 100 K (see Fig. 1, curve *6*). As in [8], the studied samples had high leakage currents in the gate–substrate circuit, which prevented direct determination of the concentration of overflowing ions as the integral of the current in this circuit over time. Therefore, despite the known limitations of the accuracy of this approach (see [3]), we rely on data on the voltage bias of the channel opening at 200 K and consider the accumulation of 6.5 × 10^{11} ions per cm^2 of this contact at the Si–SiO$_2$ interface to be the result of polarization.

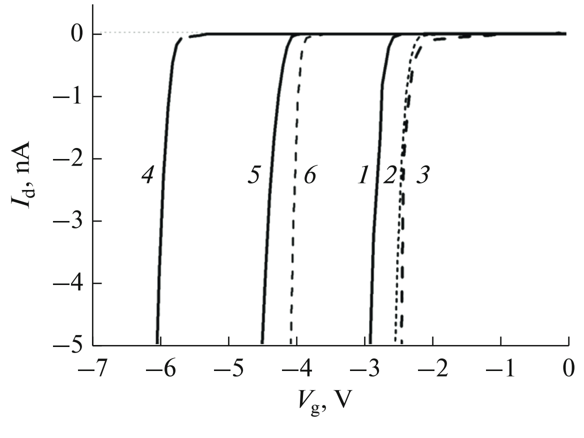

Fig. 2. Fragment of curves *1–6* shown in Fig. 1 corresponding to region of channel opening.

Figure 3 shows the temperature dependences of the effective hole mobility μ in the polarized and depolarized states. After polarization, quantity μ is significantly less than after depolarization; for a temperature of 200 K, the relation is 395 cm^2/V s compared to 800 cm^2/V s. During cooling, the mobility increases in the polarized state according to the law $\mu \propto T^{-1.6}$ and at 100 K it reaches 1270 cm^2/V s ; $\mu \propto T^{-0.9}$ and

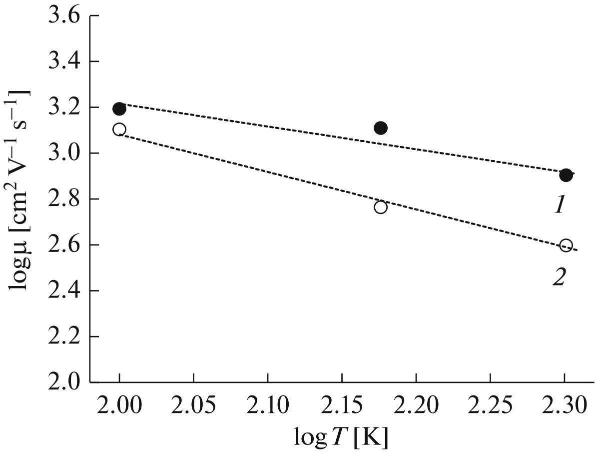

Fig. 3. Temperature dependences of effective hole mobility μ(*T*) in inversion channel of MOS transistor on double logarithmic scale after depolarization (*1*) and polarization (*2*).

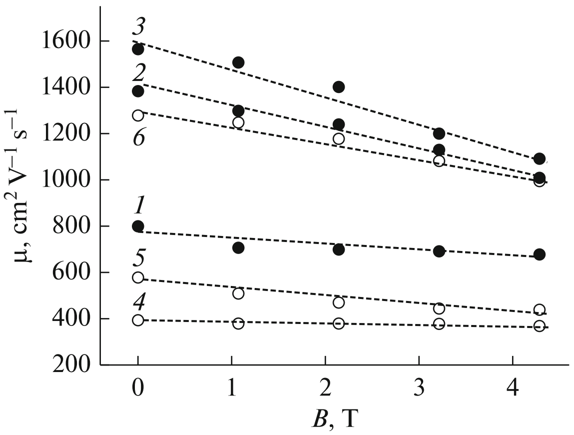

Fig. 4. Dependence of effective hole mobility μ in inversion channel of MOS transistor on magnetic field *B* at temperatures of 200 (*1*, *4*), 150 (*2*, *5*), and 100 K (*3*, *6*) after depolarization (*1*–*3*) and polarization (*4*–*6*).

1560 cm^2/V s, respectively, in the depolarized state. Such a behavior of the effective mobility in the inversion channel is characteristic of a mixture of two free charge carrier scattering mechanisms: by acoustic phonons and by charged impurities and traps [14]. The conclusion on the realization of electric transfer by free holes agrees with the condition for determining μ in the domain of field strengths far from the channel opening threshold.

Figure 4 shows the dependences of the effective mobility in the inversion channel of the transistor on the magnetic field in the range of 0–4.5 T. Both in the depolarized and polarized states, these dependences are relatively weak: at 200 and 150 K with increasing magnetic field, the effective mobility decreases by 6–20%, and at 100 K, by 20–30%. The magnetic field hardly changes the opening threshold for the inversion channel. Such a behavior of the surface conductivity is characteristic of galvanomagnetic phenomena in nondegenerate gases of free charge carriers in the case of relatively weak nonquantizing magnetic fields [15]. This conclusion is confirmed by specific experimental data: in a magnetic field $B = 4.5$ T, the diameter of the main cyclotron orbit is 12 nm, which is longer than the mean free path of holes in Si, and the value of parameter $\mu \times B$ is 0.36 (200 K), 0.62 (150 K), 0.7 (100 K).

Thus, after ionic polarization of the insulating layers of *p*-channel Si–MOS transistors at the Si–SiO$_2$ interface, an additional positive built-in charge accumulates with a concentration of 6.5×10^{11} cm^{-2}. For small field strengths up to to opening of the inversion channel, the conductivity in the source–drain circuit is achieved due to thermal activation of the charge carriers to the leakage level in the unordered potential related to the random distribution of ions along the interface [16]. The channel opens at the intersection of the Fermi level of holes on the surface of a semiconductor with the flow level in the chaotic potential. At sufficiently large voltages V_g, surface inhomogeneities of the built-in charge are largely shielded by free holes, and ions manifest themselves in the form of additional scattering centers. Therefore, the real mobility of free charge carriers and the effective mobility in the transistor inversion channel after polarization are substantially less than after depolarization. It should be noted that the polarized state of the oxide is quite stable and persists for a long time (more than a month) at temperatures below 250 K even after depolarizing voltages are applied to the field electrode. This can be used to develop and create an element base for recording and erasing devices.

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