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PHYSICS OF SEMICONDUCTOR DEVICES

On the Nature of the Increase in the Electron Mobility in the Inversion Channel at the Silicon–Oxide Interface after the Field Effect

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Abstract—The conduction characteristics of the inversion channel of Si-transistor structures after the ionic polarization and depolarization of samples are measured in (0–5)-T transverse magnetic fields at temperatures from 100 to 200 K. After ionic polarization in a strong electric field at 420 K, no less than 6×10^{13} cm^{-2} ions flowed through the oxide. The previously found tenfold increase in the conductivity in the source–drain circuit after the polarization of insulating layers is explained by the formation of a new electron transport path along the surface impurity band, related to delocalized D^- states; these states are generated by neutralized ions located in the insulating layer at its interface with the semiconductor.

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1. INTRODUCTION

The ionic polarization of insulating layers is an important tool for modifying the electronic properties of interfaces in metal–insulator–semiconductor (MIS) structures. Polarization not only shifts the threshold opening voltages of inversion channels due to the accumulation of built-in charge [1] but also changes significantly the band structure of conducting paths in view of the formation of localized impurity states at the semiconductor–insulator interface in a high concentration [2, 3]. We note also that a regular localized-charge distribution with a two-dimensional potential profile which forms various quantum-confined nanostructures at the semiconductor surface, can be implemented [4, 5]. It was experimentally shown in [6, 7] that the ionic polarization of transistor metal–oxide–semiconductor (MOS) structures increases anomalously (several times) the effective electron mobility in the inversion channel at the Si–SiO$_2$ interface. The mechanism of the increase in conductivity in the source–drain circuit under the field effect on silicon oxide remains unclear. The purpose of this study is to clarify the mechanism of this phenomenon by analyzing a large amount of experimental data on the current–voltage characteristics of a transistor after polarization and depolarization at different temperatures and data on the change in the conduction properties of the inversion channel in magnetic fields.

2. EXPERIMENTAL

Experiments were carried out on Si-MOS transistors with an electron inversion channel (of thermal gate oxide thickness h = 1000 Å, source–drain electrode width W = 1 mm, interelectrode distance L = 10 μm). The transistors were fabricated using the standard silicon technology. Measurements were carried out on a computerized setup [8]. The oxide was polarized at the gate and drain voltages V_g = 10 V and V_d = 0.01 V, respectively, for 1 h at a temperature of 420 K. After polarization, the transistor was cooled to room temperature under constant voltages. Depolarization was carried out in the same way but at a gate voltage of V_g = –10 V. Immediately after the field and temperature effects, the sample was placed in a cryomagnetic liquid-free system, which makes it possible to measure currents and voltages in the temperature range of 6–300 K in magnetic fields of up to 8 T [9]. Since the room-temperature ion drift in strong electric fields can change the sample state, the experiments were carried out at temperatures no higher than 200 K. The transistor temperature was controlled by a Lakeshore 335 thermal controller with an error of 0.01°.

3. RESULTS AND DISCUSSION

Figure 1 shows the measured dependences of the currents through the inversion channel on the gate voltage after ionic polarization and depolarization at different temperatures. A specific feature of the samples under investigation is high leakage currents in the

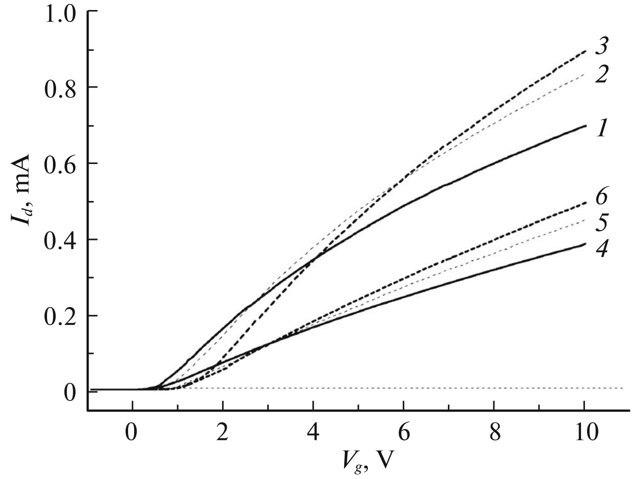

Fig. 1. Ohmic currents in the transistor inversion channel after (*1–3*) ionic polarization and (*4–6*) ion depolarization at temperatures of (*1*, *4*) 200, (*2*, *5*) 150, and (*3*, *6*) 100 K; $V_d = 0.01$ V.

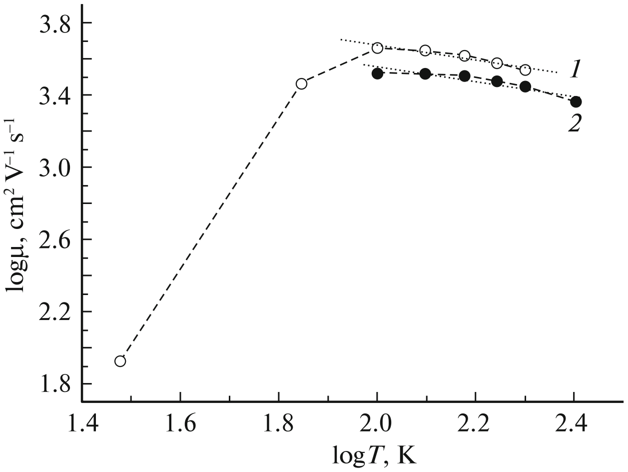

Fig. 2. Temperature dependences of the effective electron mobility in the inversion channel of a MOS transistor after (*1*) polarization and (*2*) depolarization.

gate–substrate circuit: ~5×10^{-11} A; this value is much higher than the currents related to ion drift during polarization and depolarization.[1] Nevertheless, based on the similarity of the samples and the data of [6], one can assume that no less than 6×10^{13} cm^{-2} ions are transferred through the oxide in a strong field at 420 K. Therefore, it follows from Fig. 1 that the transition from the depolarized state to the polarized state only slightly shifts the channel-opening threshold (to 0.5 V, which corresponds to 1.1×10^{11} cm^{-2} ions) in comparison with the transferred ion charge. In turn, this circumstance confirms the well-known fact of a high degree of neutralization of ions at the silicon–oxide interface [7, 10–12]. The effective electron mobility in the inversion channel is given by the formula

$$\mu = (1/C_i)d\sigma/dV_g, \tag{1}$$

where $\sigma = (I_dL/WV_d)$ is the channel's ohmic conductivity, I_d is the current in the source–drain circuit, and C_i is the capacitance of the silicon oxide gate. The μ value was determined on the portion where the current I_d depends almost linearly on the field voltage V_g. The polarization approximately doubles the effective mobility.[2] The temperature dependences $\mu(T)$ for the polarized and depolarized states are shown in Fig. 2. A decrease in the temperature is accompanied by an increase in the effective mobility; we note that $\mu \propto T^{-0.7}$ in the range of 100–200 K. With a further decrease in temperature, the μ value passes through a maximum and then drops more steeply than according to the power law. This behavior of the mobility does not correspond to the conductivity of free electrons in the inversion channel along the silicon surface [13].

Figure 3 shows the magnetic-field dependences of the effective mobility in the transistor channel in the temperature range of 100–200 K after polarization and depolarization. One can observe negative magnetic resistance: the μ value decreases with an increase in the magnetic induction from 1.07 to 4.28 T both after polarization and after depolarization, by a factor of 1.3 on average. This fact indicates the hopping character of conductivity in both polarized and depolarized states [14]. We note that the magnetic field barely changes the inversion-channel opening threshold.

The changes in the electrical conductivity of the channels along the Si–SiO$_2$ interface after the polarization of oxide saturated with sodium ions was investigated by Pepper et al. [15–18]. It was found that the aggregation of sodium ions in relatively low concentrations (~3.7×10^{11} cm^{-2}) at the Si–SiO$_2$ interface leads to the formation of upper and lower Hubbard bands (Fig. 4). The lower band is due to electronic states, whose filling leads to the neutralization of sodium ions. This band is located several tens of meV below the bottom of the silicon conduction band. The upper Hubbard band, which is due to the entanglement and delocalization of the D$^-$ states[3] formed by the potentials of neutral ionic complexes, is spaced 3.9 meV from the bottom of the silicon conduction band (disregarding the quantum confinement of electrons in the inversion channel). In our experiments,

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[1] Similar results (however, in a smaller volume) were obtained in [6] for similar samples.

[2] Some transistors exhibited a much more pronounced increase in the effective channel mobility after polarization (up to ten times), and the μ value exceeded the electron mobility in the silicon bulk.

[3] There is a perfect analogy with the D$^-$ centers formed by neutral donors in the semiconductor bulk [19].

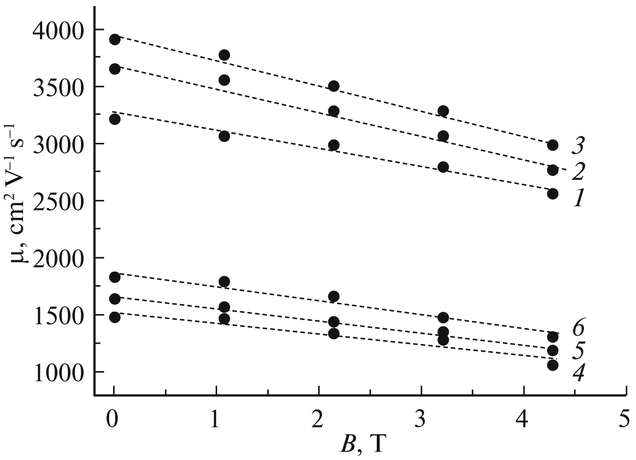

Fig. 3. Magnetic-field dependences of the effective electron mobility in the inversion channel after (*1–3*) polarization and (*4–6*) depolarization at temperatures of (*1*, *4*) 200, (*2*, *5*) 150, and (*3*, *6*) 100 K.

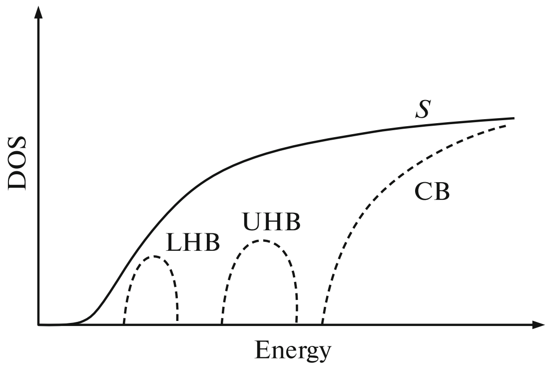

Fig. 4. Density of states in the transistor inversion channel after polarization. The dotted curves are taken from Fig. 1b in [16]. LHB and UHB denote the lower and upper Hubbard bands, respectively; CB is the conduction band; and *S* is the density of states in the inversion channel after polarization of our samples.

the number of charged particles at the Si–SiO$_2$ interface after transistor polarization is smaller by more than two orders of magnitude than in the samples investigated in [15–18]. This means (see Fig. 4) that the ion-related impurity Hubbard bands in our samples are significantly broadened and overlapped, both with each other and with the inversion-channel conduction band near the silicon surface, in comparison with the objects studied in [15–18]. In fact, the density of states S is described by a single curve, which increases steadily with energy E and finally merges with the curve describing the density of states of free electrons in the conduction band (Fig. 4). The S value and, consequently, the conductivity over delocalized states, which increase sharply as a result of polarization, make the effective mobility in the transistor inversion channel increase. The relatively weak and nonmonotonic temperature dependence of the effective mobility (Fig. 2) indicates a non-activation conductivity mechanism and thus confirms the absence of gaps in the spectrum of the density of states. A negative magnetic conductivity, indicative of the hopping nature of transport, is experimentally observed (Fig. 3); however, it depends weakly on the magnetic induction. The point is that the characteristic cyclotron radius (magnetic length) after the polarization is almost an order of magnitude larger than the average interimpurity distance, even in maximum magnetic fields in the range under consideration. Therefore, there is not any significant contraction of the electron wave functions in the band of ion-related states in a magnetic field. Therefore, the influence of magnetic induction on electron transport through the transistor inversion channel is also weak.

4. CONCLUSIONS

Thus, it was found that ionic polarization of the oxide makes it possible to change radically the electronic properties of the Si–SiO$_2$ interface. A sharp increase in the ion concentration at the silicon–oxide interface leads to the formation of a broad energy band of delocalized impurity states in the inversion channel. Electron transport over this band increases significantly the electron conductivity along the Si–SiO$_2$ interface and, correspondingly, the effective electron mobility. The polarized state of the oxide is rather stable: it is retained for a long time (more than a month) at temperatures below 250 K, even after applying depolarizing voltages to the field electrode. This property of insulating layers in silicon transistors suggests the possibility of using the processes of SiO$_2$ polarization and depolarization for recording and erasing in data-processing devices, as was proposed in [7, 20].

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