The manifestation of rising of the impurity density of states after the field stress in increasing of the effective electron mobility in the inversion channel at the silicon-oxide contact

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ABSTRACT

Measurements of characteristics of the inversion channel conductivity of MOS-transistors after the ion polarization and depolarization of samples in the range of values of the induction of the transverse magnetic field of 0 – 5 T at temperatures from 100 K to 200 K were carried out. After the ionic polarization at 420 K under the action of a strong electric field in the oxide at least $6 \cdot 10^{13}$ cm^{-2} ions flowed. The previously observed increase of the conductivity in the source-drain circuit after the polarization of insulating layers is up to 10 times explained by the formation of a new electrical transfer path through the surface impurity band, associated with delocalized D^{-} states, that are generated by neutralized ions located in the insulating layer at the interface with a semiconductor.

Keywords: the ionic polarization of insulating layers, impurity localized states, the neutralization of ions at the silicon-oxide interface, the electronic inversion channel, upper and lower Hubbard impurity bands, D^{-} states.

1. INTRODUCTION

The ionic polarization of insulating layers is an important tool for modifying of electronic properties of interfaces in metal-oxide-semiconductor (MOS) structures. Consequences of the polarization are not only shifts in threshold voltages of opening of inversion channels due to the accumulation of the built-in charge [1], but also deep changes of the band structure of conducting paths in connection with the formation of a high concentration of impurity localized states at the semiconductor-insulator interface [2, 3]. We also point out the possibility of creating a regular distribution of a localized charge with a two-dimensional potential relief, forming various quantum-size nanoscale regions near the surface of a semiconductor [4, 5]. Earlier, [6, 7] it was found, that the ionic polarization of Si-MOS structures leads to an anomalously high (several times) increase of the effective electron mobility of μ in the inversion channel at the Si-SiO_2 interface. At the same time, the mechanism of increasing the conductivity in the source-drain circuit after a field effect on silicon oxide has so far remained unclear. In this paper, an explanation of the nature of this phenomenon is given on the basis of an analysis of the large volume of experimental data on current-voltage (I-V) characteristics of a transistor in states after the polarization and the depolarization at different temperatures and on the change in conductive properties of inversion channel under the action of magnetic fields.

2. EXPERIMENTS AND DISCUSSIONS

Experiments were conducted on Si-MOS transistors with an electronic inversion channel and with the thickness of the thermal gate oxide of the h = 1000 Å, the width of electrodes of the source-drain of the W = 1 mm and the distance between them of the L = 10 μm. Transistors are formed by the standard silicon technology, but without operations, involving procedures for cleaning the oxide from impurities. This made it possible to obtain samples with a high content of mobile ions (mainly Na) in insulating layers. Measurements were carried out on a computerized installation [8]. The oxide polarization was carried out at the gate voltage of the $V_g = 10$ V and at the drain voltage of the $V_d = 0.01$ V for one

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hour at 420 K. After the completion of the polarization at constant voltages, the transistor cooled to the room temperature. The depolarization was carried out similarly, but at a voltage of the gate

$V_g = -10$ V. The sample was placed in a cryomagnetic liquid-free system, which allows to measure currents and voltages in the temperature range from 300 K to 6 K and in magnetic fields up to 8 T [9], immediately after field and temperature effects. Experiments were carried out at the temperature no higher than 200 K, since at the room temperature in strong electric fields the drift of ions can change the state of samples. The temperature of the transistor was controlled, using a Lakeshore 335 thermostat with an accuracy of 0.01 degrees.

Dependences of currents in the inversion channel on the gate voltage after the ion polarization and depolarization, respectively, at different temperatures is shown in Figure 1. From early studies [2], it is known, that energies of electronic states on concentrated in an oxide of Na ions in contact with silicon lie below the bottom of the conduction band of the semiconductor by about 0.1 eV. Therefore, at temperatures above 100 K, the recharging of these impurity centers occurs in less than millisecond times. This is significantly less than the measurement time of current-voltage characteristics. Therefore, phenomena of the type of hysteresis loops, associated with the non-stationarity of the conditions of the experiments, were practically not observed. A specific feature of studied samples are high leakage currents in the gate – substrate circuit, approximately $5 \cdot 10^{-11}$ A, which is substantially higher than currents, associated with the ion drift during the oxide polarization and depolarization, respectively.

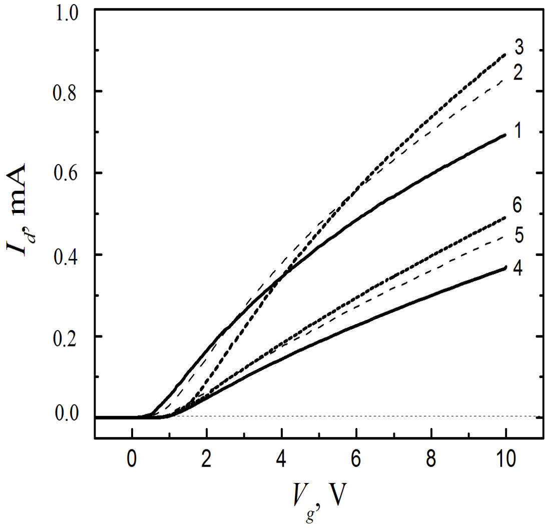

Figure 1. Ohmic currents in the inversion channel of the transistor after the ion polarization (curves 1 – 3) and depolarization (curves 4 – 6); curve numbers: 1, 4 – 200 K; 2, 5 – 150 K; 3, 6 – 100 K; $V_d = 0.01$ V.

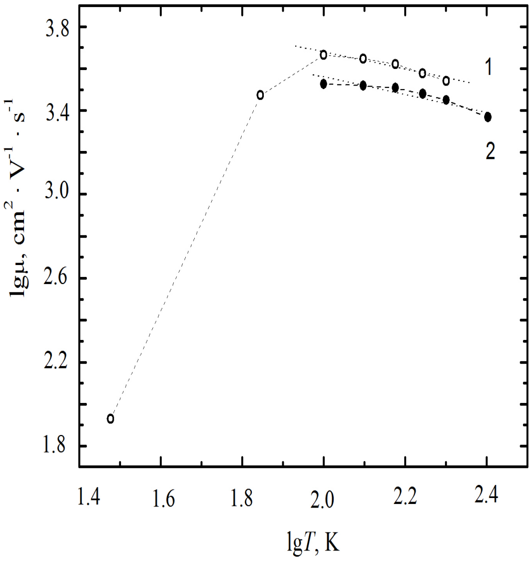

Figure 2. Temperature dependences of the effective electron mobility in the inversion channel of a MOS transistor: 1 – after the polarization, 2 – after the depolarization.

Nevertheless, based on the similarity of samples and the data, obtained in [6], it can be considered, that at a temperature of 420 K under the action of a strong field in the oxide, at least $6 \cdot 10^{13}$ cm^{-2} ions flow. Therefore, from the Figure 1a it follows, that the transition from the depolarized to the polarized state is relatively weak shifts the channel opening threshold, compared to the flowed ionic charge (to 0.5 V, which corresponds to the number of ions of $1.1 \cdot 10^{11}$ cm^{-2}). This circumstance, in turn, confirms the well-known fact about the high degree of the neutralization of ions at the silicon-oxide interface [7, 10–12]. The effective electron mobility in the inversion channel:

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

Where $\sigma = (I_d L / W V_d)$ is the ohmic conduction of the channel, I_d is the current in the source-drain circuit, C_i is the capacity of the gate oxide. The value μ was determined at the site, where the I_d current was almost linearly dependent on the V_g field voltage. The oxide polarization increases the effective mobility by about 2 times. In individual transistors, the increase in the effective mobility of the channel after the polarization was noticeably greater, up to 10 times, and the value exceeded the value of the electron mobility in the silicon bulk. Note, that the expression of (1) should lead to the true mobility under two conditions: the conduction in the channel is provided by free charge carriers, and their concentration is determined by the field effect. In our case, after the polarization, an impurity band arises and electrons, associated with the neutralization process with positively charged Na ions, also participate in the conductivity. If the concentration of neutralized particles significantly exceeds the number of free electrons per unit area of the channel, then the effective mobility may be higher than the electron mobility in the free band. Temperature dependences of $\mu(T)$ for polarized and depolarized states are shown in Figure 2. A decrease of the temperature is accompanied by an increase in the effective mobility value, and in the range of 100 – 200 K, $\mu \propto T^{-0.7}$. With a further decrease of the temperature, the μ value passes through a maximum and then drops more sharply, than in a power-law manner. This behavior of the mobility does not correspond to the conductivity of free electrons in the inversion channel along the silicon surface [13].

Dependences of the effective mobility in the transistor channel on the magnitude of the magnetic field in the temperature range of 100 – 200 K in the states after the polarization and the depolarization are shown in Figure 3. A negative magnetoconducting is observed: the μ value decreases with increasing magnetic induction from 1.07 to 4.28 T both after the polarization and after the depolarization by an average of 1.3 times. This fact testifies to the hopping nature of the conductivity in both polarized and depolarized states [14]. In this case, the magnetic field practically does not change the threshold for opening the inversion channel.

Changes in the channel conductivity along the Si-SiO$_2$ interface after the polarization of the oxide, saturated with sodium ions, were studied by the Pepper group [15–18]. It was found, that the concentration of relatively small concentrations of sodium ions of about $3.7 \cdot 10^{11}$ cm^{-2} at the Si-SiO$_2$ interface leads to the formation of upper and lower Hubbard impurity bands (see Figure 4).

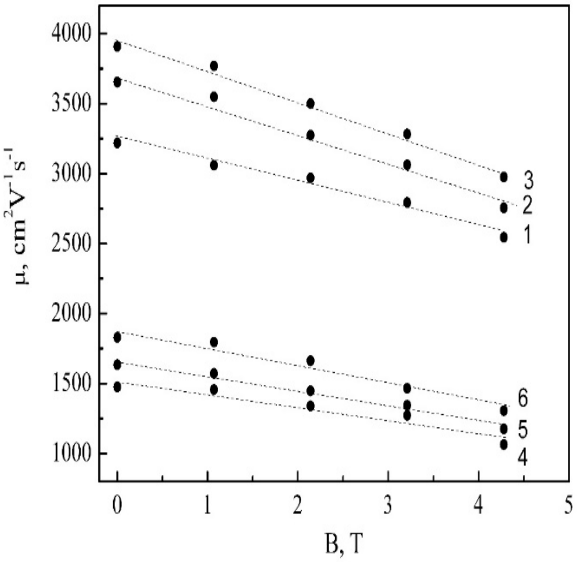

Figure 3. Dependences of the effective electron mobility in the inversion channel on the magnetic field after the polarization (curves 1 – 3) and the depolarization (curves 4 – 6); curve numbers: 1, 4 – 200 K; 2, 5 – 150 K; 3, 6 – 100 K.

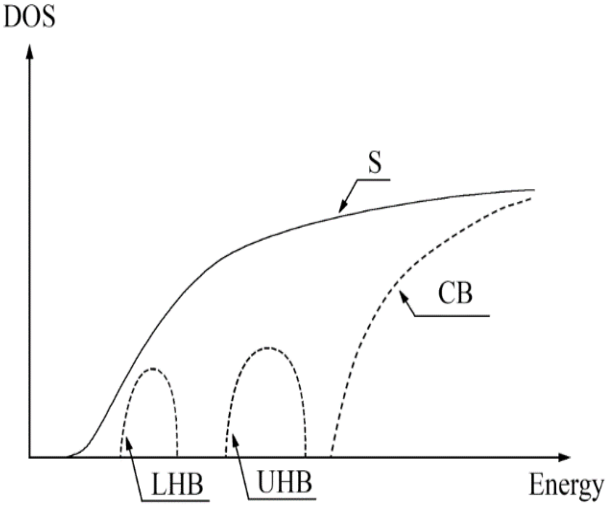

Figure 4. The type of state density of in the inversion channel of the transistor after the polarization. Dotted lines are lines, contained in Figure 1b from [16]. LHB is the lower Hubbard band, UHB is the upper Hubbard band, CB is the conduction band, S is the state density in the inversion channel after the polarization of our samples.

Electronic states are responsible for the lower band, filling of which leads to the neutralization of sodium ions. This band is located several tens of meV deeper than the bottom of the conduction band of a silicon. The upper band is caused by the entanglement and the delocalization of D$^-$ states, formed by potentials of neutral ionic complexes, and it is 3.9 meV away from the boundary of the conduction band of a silicon (without taking into account dimensional quantization of electrons in the inversion channel). A complete analogy with D$^-$ centers, formed by neutral donors in the bulk of a semiconductor [19]. The detection of two impurity bands made it possible to explain mutually contradictory experimental facts: on the one hand, the shift of the threshold of the current-voltage characteristic of the channel after the polarization of the structure is very small and not comparable with the number of impurities, concentrated at the semiconductor-insulator interface. This indicates that impurities are almost completely filled with electrons. On the other hand, a sharp increase in the effective mobility, determined by the field effect, indicates an increase of the conductivity of the surface band with increasing concentration of free electrons in the channel. This fact corresponds to a weak filling of the impurity band with electrons. The contradiction disappears for two impurity bands: the lower band, which is responsible for the neutralization of ions, is almost filled, and the upper band, which is conducting, is almost empty. In our experiments, after the polarization, it turns out to be at least two orders of magnitude more charged particles at the Si-SiO$_2$ interface than in the samples, studied in [15–18]. This means (see Figure 4) that, in the comparison with objects of measurements of the Pepper group, in our samples Hubbard impurity bands, associated with ions, are substantially broadened and overlapped both with each other and with the conduction band of the inversion channel near the silicon surface. In fact, the state density of the $\boldsymbol{S}$ is described by a single, monotonically increasing curve with the energy of the $\boldsymbol{E}$, which eventually merges with the graph of the state density of free electrons in the conduction band (see Figure 4). The magnitude of the $\boldsymbol{S}$ and, consequently, the conductivity according to delocalized states, which increase sharply as a result of the polarization, ultimately explain the increase of the effective mobility in the inversion channel of the transistor. The relatively weak and non-monotonic dependence of the effective mobility on the temperature (see Figure 2) indicates a non-activation mechanism of the conductivity and thus confirms the absence of gaps in the spectrum of the state density. The experiment shows (see Figure 3), although negative magnetoconducting, indicating a jump-like character of the transport, but with a weak dependence on the magnitude of the magnetic induction. The fact is that after the polarization, even with maximum values of magnetic fields used by us, the characteristic radius of the cyclotron orbit (magnetic length) turns out to be almost an order of the magnitude higher than the average interimpurity distance. Therefore, no significant compression in the magnetic field of wave functions of electrons in the band of states, associated with ions, does not occur. Accordingly, the effect of the magnetic induction on the transport of electrons along the inversion channel of the transistor is insignificant.

3. CONCLUSIONS

Thus, the ionic polarization of the oxide makes it possible to radically change of electronic properties of the Si-SiO$_2$ interface. A sharp increase in the concentration of ions at the contact of a silicon with an oxide leads to the formation of a wide (in energy) band of delocalized impurity states in the inversion channel. As a result, of the transport of electrons in this band, the conductivity significantly increases along the Si-SiO$_2$ interface and its characteristic value – the effective electron mobility. The polarized state of the oxide is stable enough and for a long time (more than a month) is maintained at temperatures below 250 K even after depolarizing voltages, are applied to the field electrode. This property of insulating layers in silicon transistors suggests, that the use of SiO$_2$ polarization and depolarization phenomena as recording and erasing processes in information processing devices, proposed in [7, 20]. In fact, transistors with a fairly high content of mobile ions in the insulating layers are devices with tunable characteristics of conducting channels. This property makes it possible to use these objects as elements of a wide variety of electronic circuits, for example, modeling operation of neural systems.

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