ISSN 1063-7826, Semiconductors, 2021, Vol. 55, No. 1, pp. 21–24. © Pleiades Publishing, Ltd., 2021.
Russian Text © The Author(s), 2021, published in Fizika i Tekhnika Poluprovodnikov, 2021, Vol. 55, No. 1, pp. 24–27.

SURFACES, INTERFACES, AND THIN FILMS

Silicon Ultrathin Oxide (4.2 nm)–Polysilicon Structures Resistant to Field Damages

D. A. Belorusov[a], **E. I. Goldman**[a], **V. G. Naryshkina**[a], **and G. V. Chucheva**[a],*
[a] *Kotelnikov Institute of Radioengineering and Electronics, Fryazino Branch, Russian Academy of Sciences, Fryazino, Moscow oblast, 141190 Russia*
**e-mail: gvc@ms.ire.rssi.ru*

Received August 24, 2020; revised September 2, 2020; accepted September 2, 2020

Abstract—The results of investigations of silicon–ultrathin oxide (42 Å)–polysilicon structures resistant to field damages are presented. It is found that the total charge exchange of localized electronic states and minority charge carriers concentrated at the substrate–insulator interface, which occurs with a change in the field voltage, is close to the same characteristic of structures with an oxide thickness of 37 Å. The current flowing through SiO_2 increases with voltage much stronger in the enrichment state of the semiconductor than in its depletion state. Moreover, the asymmetry of the *I*–*V* characteristics with respect to the polarity of the voltage drop across the insulator in SiO_2 samples with a thickness of 42 Å is more pronounced than in structures with an oxide of 37 Å. An explanation for this asymmetry is possible, if the potential relief in the insulator has a peak, which is significantly shifted to the oxide–polysilicon interface, and the potential on the branch on the semiconductor side significantly decreases towards the contact with the substrate.

Keywords: metal–insulator–semiconductor structures, ultrathin oxide, field damage, high-frequency *C*–*V* characteristics, *I*–*V* characteristics

DOI: 10.1134/S1063782621010036

1. INTRODUCTION

Ultrathin (<5 nm) oxide films are the primary type of insulating layers in modern and future nanoscale devices. Due to their small thickness, the electric fields arising in such layers under control actions on the active elements of modern semiconductor devices reach several units of 10^6 V/cm. At these field values, significant leakage currents arise in SiO_2, and the phenomena responsible for changing the properties of the insulating gap, both reversible, so-called “oxide damage”, and irreversible soft breakdown, take place. We emphasize that, despite the pre-breakdown values of the indicated electric fields, the probability of sample transition to the irreversible state of soft breakdown still arises with an increase in action duration [1, 2]. In our group, we have already investigated the changes in the properties of ultrathin oxides after damage of Si-MOS (metal—oxide–semiconductor) structures in electric fields for more than ten years [3–5]. We have found [6] that there is a group of samples with an oxide thickness $h = 37$ Å in which there is practically no reaction to the damaging field action; i.e., neither the conductivity through the oxide, nor the distribution of the built-in charge are practically changed with increasing duration of exposure at field voltages of different polarity up to transition to the state of soft breakdown in objects. The natural problem is how common is the property of “undamageability” in ultrathin oxides under stresses in electric fields. To resolve this, we turn to objects with a different oxide thickness of $h = 42$ Å prepared according to the same technological scheme as in [6]. We use as samples Si-MOS structures with an Al-n^+-Si:P field electrode (the concentration $N_d^+ \approx 10^{20}$ cm^{-3} of donors in polysilicon; the field-electrode area $S = 1.6 \times 10^{-3}$ cm^2) insulated from the (100) n-Si substrate by a SiO_2 layer with an optical thickness of ~4.2 nm obtained by high-temperature oxidation.

2. EXPERIMENTAL AND RESULTS

The structures were subjected to field stresses at room temperature and the same field voltage V_g as in investigations of the damage of ultrathin SiO_2 [3, 5].[1] The field voltage was $V_g = -3.8$ V (substrate depletion) at the shortest exposure time of 16 min, and $V_g = 3.2$ V (substrate enrichment) at the shortest exposure time of 20 min. Before and after the stress, we measured the *I*–*V* characteristic and the high-frequency *C*–*V* char-

---

[1] The decrease in the field value in the oxide in comparison with experiments [6] was no more than 13%, which is not significant for the purposes of investigations.

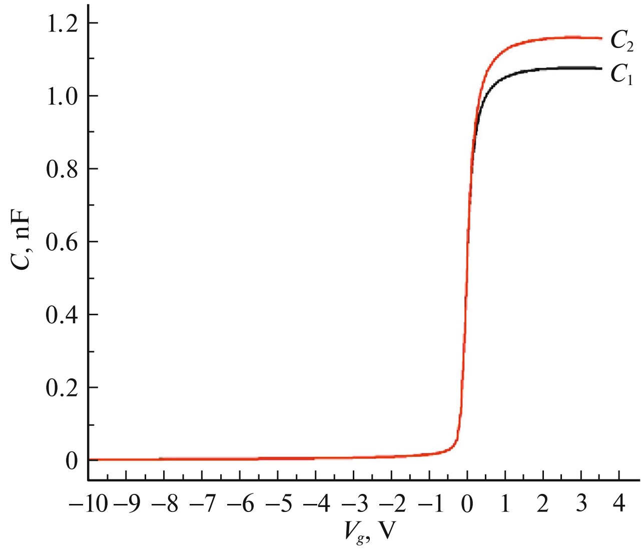

Fig. 1. High-frequency *C*–*V* dependences of the samples measured at room temperature. Capacitances: C_1 at 1 MHz and C_2 at 0.5 MHz.

acteristic of the objects at frequencies of 1 (C_1) and 0.5 (C_2) MHz using an Agilent E4980A precision LCR meter on an automated installation [4]. The results of the investigations carried out are presented in this study.

It turned out that the samples selected by us as well as structures with a thinner oxide [6] are stable to field actions. Measured immediately after stress, the *I*–*V* and *C*–*V* characteristics were almost indistinguishable from the corresponding characteristics measured before ageing the objects in an electric field: the discrepancies were no more than 2%, in contrast to structures [5], where a decrease in the capacitances was several times after removal of the damaging voltage. In [6], we found significant asymmetry of the *I*–*V* characteristic: at voltages close in modulus, the currents in the region of strong depletion of the semiconductor were orders of magnitude lower than in enriched silicon. To understand whether or not this property is inherent for objects with an oxide thickness of 42 Å, we measured the *I*–*V* and *C*–*V* characteristics by analogy with [6] in a special mode, when the high-frequency capacitance and current values correspond to the same state of the sample. We repeat the essence of the experiment schemes. For each measurement point, set V_g was applied to the sample from the position with the field voltage $V_g = 0$; after termination of the RC processes (<0.3 s), the current *I* was detected first through the oxide, then, through the capacitors C_1 and C_2 for 3 s. After that, the applied voltage was dropped to zero, and the structure was aged for 6 s. The total duration of measurements of the currents and capacitances at the same voltage value applied to the field electrode (6 s) is significantly less than the characteristic time of the transient process associated with the charge exchange of localized electronic states at the Si–SiO$_2$ interface (>100 s). This procedure enables us to minimize the duration of sample exposure to stress conditions in the measurements. The data of *C*–*V* characteristics corresponding to two high frequencies make it possible to determine the donor concentration N_d near the Si–SiO$_2$ interface, the resistance R_b of the semiconductor substrate, and the field-voltage dependence for the following quantities: the band bending V_s in the semiconductor, the external voltage drop V_i on the insulating layer, and the total density of the built-in charge expressed in cm^{-2}, and the charge p_{sq} of boundary states and holes at the interface [4, 5, 7].

In Fig. 1, we show the dependences of the sample capacitances on the voltage measured at room temperature in the state before the field stress. Calculations based on of the data of the *C*–*V* characteristics according to the method described in [5, 7] led to the following values: $N_d = 1.65 \times 10^{15}$ cm^{-3} and $R_b = 73\ \Omega$. These values are almost the same as those obtained in [6]: $N_d = 1.65 \times 10^{15}$ cm^{-3} and $R_b = 88\ \Omega$. The $p_{\text{sq}}(V_g)$ plot is shown in Fig. 2; the flat-band state corresponds to the voltage $V_g = -0.19$ V. It can be seen that curves demonstrating the charge exchange of the Si–SiO$_2$ interface in objects with an oxide thickness of 4.2 nm (this study) and 3.7 nm [6] are close to each other: as V_g varied from –0.5 to –6 V, the increase in p_{sq} was $\Delta p_{\text{sq}} = 1.0 \times 10^{13}$ cm^{-2} at $h = 42$ Å and $\Delta p_{\text{sq}} = 1.4 \times 10^{13}$ cm^{-2} at $h = 37$ Å. The Δp_{sq} values are an order of magnitude higher than those in the damaged structures [5, 8]. As in [6], it turned out that $V_i \propto V_g/2$ means that the measurements were carried out in a nonstationary and nonequilibrium, with respect to minority charge carriers (the hole generation is delayed), state of the sample in the semiconductor depletion region.

In Fig. 3, we show the dependences of the current through the oxide on the voltage drop across the insulating layer at positive (the injection of electrons from the semiconductor) and negative (the injection of electrons from the field electrode) polarities of V_g. For clarity, the *I*–*V* characteristics are shown in linear and logarithmic scales. Here $V = V_g$ for $V_g > 0$ and $V = -V_i$ for $V_g < 0$; the graphs of the current branches in the logarithmic scale were plot according to the rule: $\varphi_+(V) = \log[I(V_g)/I_n]$ is for $V_g > 0$, $\varphi_-(V) = \log[I(V_i)/I_n]$ for $V_g < 0$, where I_n = 10–12 A is the normalizing current value. It should be noted that the charge-exchange currents $qS(dp_s/dt)$ (q is the elementary charge, and t is the time) is 1.5–2 orders of magnitude lower than *I*. It follows from the measurements of the

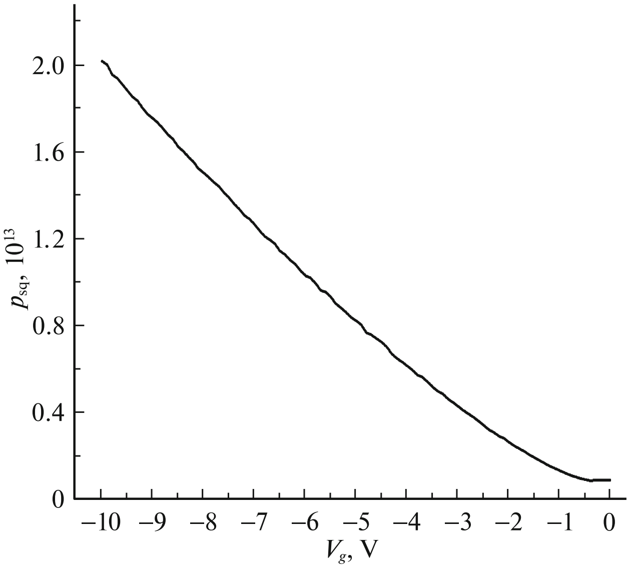

Fig. 2. Dependence of the total density of the built-in charge and the charge of boundary states and holes at the Si–SiO_2 interface on the field voltage.

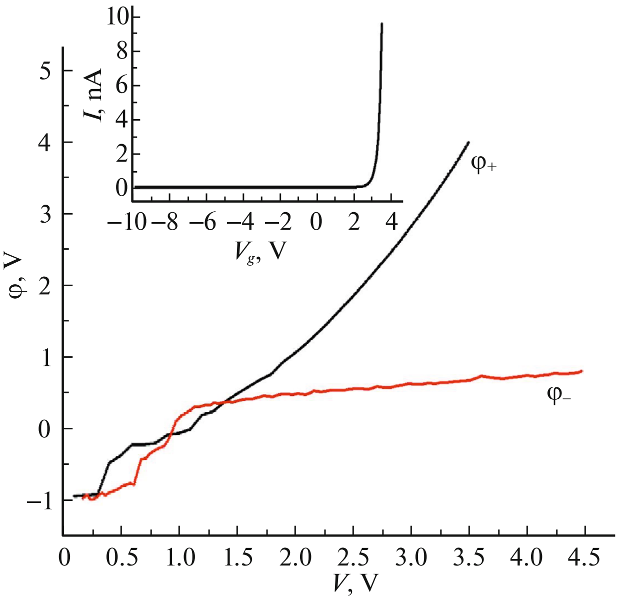

Fig. 3. I–V characteristics of the insulating gap of Si-MOS structures measured at room temperature. φ(V) is the function of the logarithm of current versus the voltage applied to the oxide. The inset shows the dependence of the current on the field voltage in real scale.

transient-current characteristics and the capacitances at several voltages V_g. From Fig. 3, it can be seen that the asymmetry of the I–V characteristic with respect to the polarity of the voltage dropped at the insulator for the samples with a SiO_2 thickness of 42 Å is more pronounced than that of the structures with an oxide of 37 Å. For the objects from this study, the current increases by 5 orders of magnitude in the semiconductor enrichment state within the voltage range of (0–3.5) V and by only one order of magnitude in the depletion state. For the samples from [6], this ratio was 5/3.

3. CONCLUSIONS

Thus, it can be stated that, at least for certain ultrathin SiO_2 layers obtained in the case of the high-temperature oxidation of silicon, the property of resistance to field damaging actions is typical. Revealing the nature of this is possible only when setting a series of special joint technological and physical investigations and is not the purpose of this study. We discuss the features of the insulating layers, which are the basis of another property of such objects, namely, the asymmetry of the I–V characteristic with respect to the polarity of the external voltage. For ultrathin oxide films, an important circumstance is the non-rectangular shape of the potential barrier formed by the insulating gap. Since the transition layers between crystalline Si and SiO_2, as well as between the oxide and the field electrode from poly-Si, occupy at least 40% of the volume of the ultrathin dielectric [9], they actually largely determine the properties of the insulator. The transitions from the substrate to the oxide and from the oxide to the polysilicon are formed in different technological processes and have a different crystalline structure. Therefore, it is natural to expect also different (asymmetric) coordinate dependences of the potential insulating profile on these contacts. To explain the asymmetrical form of the I–V characteristics, it should be assumed that the potential relief in the insulator has a peak, which is significantly shifted to the oxide–polysilicon interface; the potential on the branch on the side of the semiconductor drops significantly towards the contact with the substrate. With this form, the barrier is “eaten away” by the electric field in SiO_2 much faster in the case of the injection of electrons from the semiconductor than from the field electrode. Exact solution of the problem on the shape of the potential in an ultrathin insulating gap should be given by forming a real relief, which separates the substrate and the field electrode, on the basis of the technique developed in [10].

FUNDING

The study was carried out within the framework of the state assignment and partially supported by the Russian Foundation for Basic Research, project nos. 18-29-11029-mk, 19-07-00271-a, and 19-29-03042-mk.

CONFLICT OF INTEREST

The authors declare that they have no conflicts of interest.

REFERENCES

1. J. S. Suehle, in *Defects in Microelectronic Materials and Devices*, Ed. by D. M. Fleetwood, S. T. Pantelides, and R. D. Schrimpf (CRC Boca Raton, FL, 2008), Chap. 15, p. 437.
2. J. Suñé and Ern. Y. Wu, in Defects in Microelectronic Materials and Devices, Ed. by D. M. Fleetwood, S. T. Pantelides, and R. D. Schrimpf (CRC, Boca Raton, FL, 2008), Chap. 16, p. 465.
3. E. I. Goldman, N. F. Kukharskaya, V. G. Narishkina, and G. V. Chucheva, Semiconductors **45**, 944 (2011).
4. E. I. Goldman, A. I. Levashova, S. A. Levashov, and G. V. Chucheva, Semiconductors **49**, 472 (2015).
5. E. I. Goldman, S. A. Levashov, V. G. Naryshkina, and G. V. Chucheva, Semiconductors **51**, 1136 (2017).
6. E. I. Goldman, S. A. Levashov, and G. V. Chucheva, Semiconductors **53**, 465 (2019).
7. E. I. Goldman, N. F. Kuharskaya, S. A. Levashov, and G. V. Chucheva, Semiconductors **53**, 42 (2019).
8. E. I. Gol’dman, Yu. V. Gulyaev, and G. V. Chucheva, Radiotekhnika **8**, 58 (2015).
9. A. P. Baraban, V. V. Bulavinov, and P. P. Konorov, *Electronics of SiO2 Layers on Silicon* (LGU, Leningrad, 1988) [in Russian].
10. E. I. Goldman, A. G. Zhdan, N. F. Kukharskaya, and M. V. Chernyaev, Semiconductors **42**, 92 (2008).

Translated by V. Bukhanov