Effect of Hydrogen Implantation Dose on the Relaxation of Electrophysical Characteristics of Silicon-on-Insulator Structures after Exposure to X-rays

© N.D. Abrosimova [1], P.A. Yunin [3,¶], M.N. Drozdov [3], S.V. Obolenskii [2]

[1] Sedakov Scientific Research Institute of Measurement Systems,
603951 Nizhny Novgorod, Russia
[2] Lobachevsky University of Nizhny Novgorod,
603600 Nizhny Novgorod, Russia
[3] Institute of Physics of Microstructures, Russian Academy of Sciences,
607680 Nizhny Novgorod, Russia
[¶] E-mail: yunin@ipmras.ru

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Experimental studies of the relaxation of electrophysical parameters of SOI structures with different doses of hydrogen implantation after exposure to stationary X-ray radiation are presented. Investigation of high-frequency CV characteristics and pseudo-MOS transistors made it possible to obtain information about the accumulated charge, the density of surface states, mobility of carriers. The impurity composition and depth profile of hydrogen concentration were determined by the SIMS method. Structural perfection of the layers and interfaces was evaluated using the XRR and XRD methods. A different nature of the relaxation dependence and the recovery time of the electrophysical parameters for SOI structures with different doses of hydrogen implantation are recorded. The values of mobility and charge density are higher for the structure with a lower hydrogen implantation dose.

Keywords: Ion implantation, silicon on insulator, radiation resistance, X-ray diffraction, pseudo-MOS transistor, residual hydrogen, SIMS.

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1. Introduction

Historically, the technology of producing the „silicon-on-insulator" (SOI) structures is the first commercial technology, which is specially designed to provide for production of high-speed as well as radiation-proof integrated circuits (IC) by considerable reduction of parasite capacitances and almost full exclusion of leakage currents through the substrate between adjacent active IC elements [1–3].

The technologies of formation of the SOI structures using the hydrogen transfer and the direct bonding have a number of advantages in relation to other methods [1–3]: a) the periods of the crystal lattices of connected materials may be different; b) it is possible to manufacture multilayer structures with super-thin layers; c) it is possible to integrate digital, analogue and radiofrequency elements in one plate.

The hydrogen implantation is one of the key operations in forming these structures, which largely determines the quality of the finished structure. The doses used for splitting range from $3 \cdot 10^{16}$ to 10^{17} ions/cm^2. The thickness of a peeled-off layer may deviate from the required value for about a dozen of nanometers, and the splitting may occur not only at the maximum of the concentration of the hydrogen atoms, but at the maximum of the implantation defects. The nature and the distribution of the implantation defects also depend on the dose [4], the increase in the dose results in the increase in the density of the defects and the damaged layer.

It is generally assumed that the final high-temperature annealing of the SOI structure removes the entire hydrogen and its formed complexes. However, it is not true as demonstrated by the secondary ion mass-spectrometry (SIMS). The residual hydrogen in the SOI structure may passivate the broken bonds, modify the electric properties of point defects and change their energy levels, thereby resulting in the considerable change of the electrophysical characteristics up to the formation of the inverse conductivity layers [5–7]. When operating the SOI instruments of the complementary metal-oxide-semiconductor (CMOS) structure, in the space conditions, the technologies are the most sensitive to the absorbed dose effects. One of these effects includes accumulation of the positive charge in SiO_2 due to the difference in mobility of the electrons and the holes. The charge may be also accumulated at the SiO_2 interfaces with the substrate and the instrument layer [8,9]. It results in changing the functional characteristics of the instrument compositions (the threshold voltages of the transistor structures, the steepness of the current-voltage characteristics, the leakage currents of the transistor structures in a closed state) and the properties of the materials, in particular, the mobility of the carriers in the instrument layer, the mobility, the density of the surface states at the interfaces, the state of the impurity-defect system [10]. These effects have an ionization nature and manifest themselves at low doses and intensities of the impact. The absorbed dose effects are simulated by X-ray radiation effects [10,11]. The influence of the hydrogen implantation dose on the transformation of the impurity-defect system of the SOI structures under the ionising radiation effects may be heterogeneous and ambiguous.

The purpose of this study was to investigate the influence of the hydrogen implantation dose on the relaxation of the electrophysical characteristics of the SOI structures under the X-ray radiation effects.

2. Experimental procedure

The SOI structures had the *p*-type of conductivity. The technological modes of manufacturing the studied structures were the same except for the hydrogen implantation dose. The hydrogen was implanted with the doses from 4.5 to $7 \cdot 10^{16}\,\mathrm{cm}^{-2}$, the thickness of the instrument layer was ~ 60 nm, so was that of the concealed dielectric — 150 nm, while the orientation of the instrument layer and the substrate was — (100). The article examines the two structures: #4 with a lower hydrogen implantation dose and #5 with a higher hydrogen implantation dose.

The crystalline quality, the layer thicknesses and the interface widths in the SOI structures have been evaluated using the X-ray diffraction (XRD) and the small angle X-ray reflectometry (XRR) by the X-ray diffractometer Bruker D8 Discover. The hydrogen profile was measured using the SIMS on the IONTOF unit TOF.SIMS-5 with a time-of-flight mass analyzer. The hydrogen concentration was determined in accordance with the procedure specified in [12]. The equipment of the IPM RAS Collective Use Center was used.

The electrophysical properties have been studied by means of methods of the high-frequency voltage-capacitance characteristics (HF CVs) and a pseudo-MIS transistor by the mercury probe [13–16] before and after impact by the stationary low-energy X-ray radiation. The relaxation had been traced for two weeks since the irradiation time.

The charge and the density of the surface states at the interface with the instrument layer were determined by analyzing the current-voltage curves by the pseudo-MIS transistor, so were by analyzing the HFCVs at the substrate interface. The method of the pseudo-MIS transistor is based on the fact that the SOI plate can be represented as a model of the inverted MIS transistor: the substrate of bulk silicon acts as a gate to be fed with a shift via the metal contact in order to generate a conductive channel in the thin instrument layer [13–16]. The concealed oxide acts as the gate dielectric, while the silicon film is a „body“ of the transistor. By analyzing the drain-gate characteristics of such a transistor, it is possible to obtain the data on the density of the surface states at the interface of the silicon instrument layer and the concealed dielectric, the mobility of the carriers in the silicon instrument layer and the charge accumulated in the embedded dielectric under the II impact [13].

An undeniable advantage of this method is that the electrophysical properties of the bounding interface and the concealed dielectric can be expressly controlled in a non-destructive manner with the rich information content.

3. Results and discussion

Fig. 1 shows the typical SIMS profile of element distribution along the depth in one of the studied structures #4 (with the lower hydrogen implantation dose). As it is clear from Fig. 1, the studied SOI structures exhibit a carbon impurity and the SiN layers at the interfaces of the SiO_2 layer. The presence of SiN is apparently correlated to an oxidation atmosphere. The peaks of the SiN and C profiles are located at the surface of the instrument layer and at the interfaces of the concealed dielectric and the semiconductor, while the SiN and C concentrations are higher at the

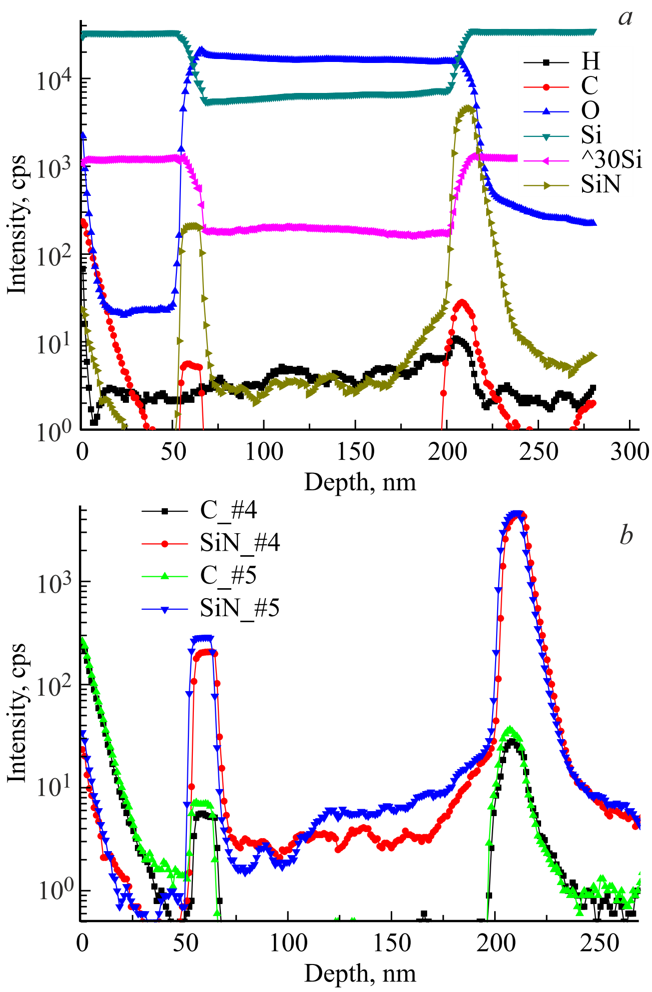

Figure 1. *a* — SIMS profiles of element distribution along the depth of the SOI structure #4; *b* — the comparison of the C and SiN profiles in the structures #4 and #5. (A color version of the figure is provided in the online version of the article).

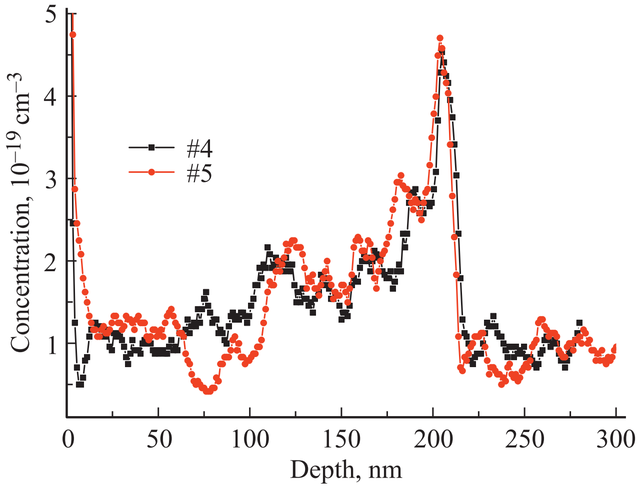

Figure 2. SIMS profiles of distribution of the hydrogen concentration along the depth of the SOI structures with the various hydrogen implantation dose.

substrate interface. Fig. 1, *b* compares the profiles of the C and SiN impurities for the structures #4 and #5. It is clear that in the structure #5 the concentration of C and N at the interface with the instrument layer in 1.5–2 times higher than in the structure #4. The interaction of carbon with point defects, in particular, with the A-centers, results in the increase in the energy of the acceptor levels and the decrease in the energy of the donor ones [17]. By passivating the A-centers, hydrogen reduces the energies of both the acceptor and donor levels. After being embedded into the lattice points, as a result of the interaction with the vacancies nitrogen is a deep donor to reduce the lattice period due to a radius smaller than that of silicon [17]. Besides, as per [18], in interaction of a small quantity of nitrogen with excessive Si-Si bonds at the Si-SiO_2 interface, there are additional defects, which are hole traps.

Fig. 2 compares the SIMS profiles of the hydrogen depth distribution in the structures #4 and #5. It is clear that the hydrogen is in the dielectric layer, to a greater extent, at the substrate interface. The difference in the hydrogen profiles for the structures with the different implantation dose can be noticed only at the interface of the concealed dielectric with the instrument layer.

The typical results of the XRR and XRD analysis of the structure #5 are shown on the figures 3, *a* and *b*, respectively. The data were processed by joint fitting of the experimental data as per a unified model of the structure [19]. The simulation results are shown in Table 1. The joint XRR and XRD analysis has shown that there is an additional layer of the density at the interface of the dielectric layer and the substrate, which is different from that of Si and SiO_2. This was interpreted as the SiN layer in accordance with the SIMS data. Indirectly, too, we can judge the presence of a thinner and less pronounced transient layer at the interface of the dielectric with the instrument Si layer based on a difference of the thickness of the instrument Si layer determined by the XRR and XRD methods. Due to their peculiarities, the XRR method is designed to determine the layer thickness by a density contrast, so is the XRD method by the oscillations of the thickness contrast of the single-crystal layer. The bigger thickness diagnosed by the XRR in comparison with the XRD can be interpreted as the presence of the transient layer at the interface of the low crystalline quality, but at the same time having an insufficient density surge for explicitly recording the correlated oscillations on the XRR curve. This results is also confirmed by the SIMS data. Within the measurement errors, it can be concluded that the structural quality of the samples #4 and #5, investigated by the XRR and XRD methods is the same, while the differences of the

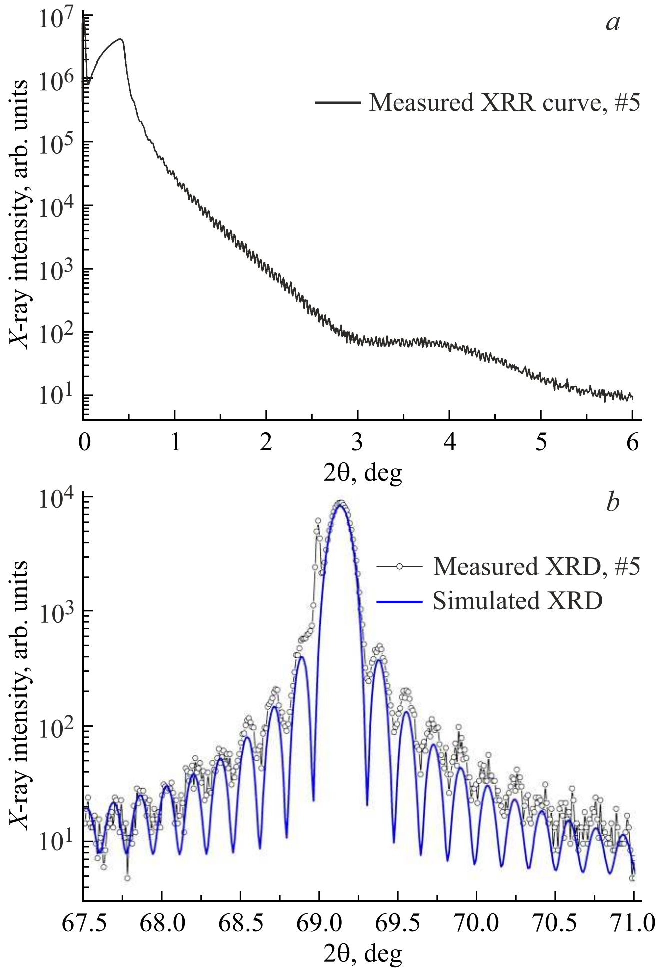

Figure 3. *a* — the curve of the small angle reflectometry for the structure #5. It is clear that there are the Kissig oscillations with three different angle periods, which correspond to the three various thicknesses: the Si instrument layer, the dielectric layer and the additional layer at the substrate interface. The simulation results are not shown to avoid confusion; *b* — the curve of the diffraction reflection (004) of the single-crystal Si instrument layer in the structure #5: the experiment (the points) and the simulation (the line).

electrophysical characteristics must be determined by the hydrogen implantation dose and the impurity composition.

It is clear from Fig. 4 that the current-voltage characteristics of the pre-irradiation SOI structures produced by the method of the pseudo-MIS transistor are not different within the hole current, but they substantially differ within the electron conductivity. The hydrogen dose for the structure #5 is approximately in two times higher for the structure #4. The lower electron current in the instrument layer of the structure #5 may be caused by the bigger number of the acceptor centers at the interface of the dielectric and the instrument layer. This is confirmed by the data of the SIMS profiles of Fig. 1, *b*, which show a large amount of carbon and nitrogen at the interface of the instrument layer and the concealed dielectric at the silicon side.

Fig. 5 shows the charge density is the highest in the first days after irradiation. For the two weeks the charge density is restoring at the interface with the instrument layer, but the charge density is not restoring at the substrate interface. Nature of rebuilding of the charge density — monotonic for the structure #4 (with the lower dose) and oscillating for the structure #5 (with the higher dose). The fixed charge and

Table 1. Comparison of the geometric parameters of the density of the layers of the SOI structures with the various hydrogen implantation doses as determined by the XRD and XRR methods

Properties	Thickness of the layers, ± 0.5 nm		Roughness ± 0.3 nm		Density, ± 0.05 g/cm^3	
Designation of the structure	#4	#5	#4	#5	#4	#5
Si XRR (XRD)	66.0 (64.0)	65.5 (64.0)	1.2	1.3	2.33	2.33
SiO_2 XRR	140.0	144.0	0.9	1.0	2.40	2.40
SiN XRR	3.2	3.2	0.3	0.4	2.50	2.50
Si (substrate)			0.3	0.6	2.33	2.33

Table 2. Relaxation of the density of the surface states at the interfaces of the concealed dielectric with the instrument layer and the substrate of the SOI structures with the various hydrogen implantation doses: *1* — the interface with the instrument layer, *2* — the interface with the substrate

t, days	D_{it}, eV$^{-1}\cdot$cm^{-2}			
	Structure #4		Structure #5	
	1	*2*	*1*	*2*
0	$2.60\cdot10^{12}$	$3.60\cdot10^{12}$	$6.30\cdot10^{12}$	$3.00\cdot10^{13}$
1	$7.00\cdot10^{12}$	$8.00\cdot10^{12}$	$2.00\cdot10^{13}$	$8.00\cdot10^{12}$
3	$7.00\cdot10^{11}$	$6.00\cdot10^{12}$	$5.00\cdot10^{12}$	$6.00\cdot10^{12}$
7	$7.00\cdot10^{11}$	$4.00\cdot10^{12}$	$2.00\cdot10^{12}$	$4.00\cdot10^{12}$
10	$6.00\cdot10^{11}$	$8.00\cdot10^{11}$	$6.00\cdot10^{11}$	$2.00\cdot10^{12}$
14	$5.00\cdot10^{11}$	$8.00\cdot10^{11}$	$8.00\cdot10^{11}$	$1.00\cdot10^{12}$

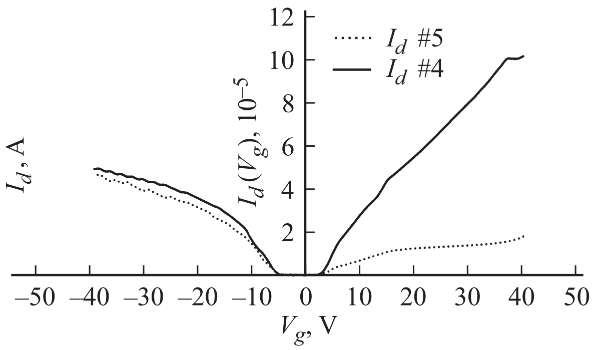

Figure 4. Drain-gate current-voltage curves of the SOI structures with the various hydrogen implantation doses, which are obtained by the method of the pseudo-MIS transistor.

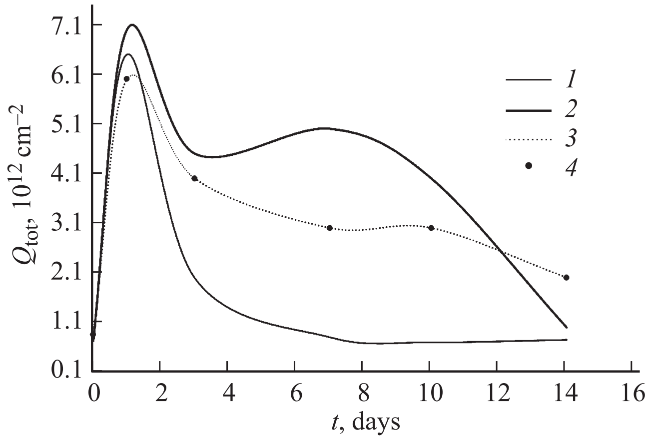

Figure 5. Charge relaxation in the SOI structures with the various hydrogen implantation dose. *1* — the charge density at the interface with the instrument layer for the structurer #4, *2* — the charge density at the interface with the instrument layer for the structure #5, *3* — the charge density at the substrate interface for the structure #4, *4* — the charge density at the substrate interface for the structure #5.

the fixed density of the surface states at the interface with the instrument layer depend on the hydrogen implantation dose, while at the substrate interface they do not depend thereon.

As it is clear from Table 2, the density of the surface states increases after irradiation, then decreases and after the two weeks its values become less than before the irradiation.

As it is clear from the data of Table 3, the mobility of the electrons and holes decreases just after the irradiation, while the carrier mobility is not restored in two weeks after the irradiation. The nature of rebuilding of the hole mobility is monotonic, while the mobilities of both electrons and holes are higher for the structure #4 (with the lower hydrogen implantation dose).

The non-monotonic relaxation is caused by competing processes of accumulation of the capture centers and scattering of the carriers in irradiation and formation of the electron generation centers in the instrument layer and,

Table 3. Relaxation of the mobility of the electrons and holes in the SOI structures with the various hydrogen implantation doses

t, days	Structure #4		Structure #5	
	μ_n, $cm^2/(B \cdot c)$	μ_p, $cm^2/(B \cdot c)$	μ_n, $cm^2/(B \cdot c)$	μ_p, $cm^2/(B \cdot c)$
0	675	210	323	210
1	60	20	30	20
3		50		50
7		100		40
10		110	70	
14	400	150	300	100

possibly, at the interface of the instrument layer and the concealed dielectric. The hydrogen, interacting with the typical defects of the Si-SiO_2 system, such as the *A*-centers, the *K*-centers, etc. as well s with the impurity atoms can modify their energy levels and, consequently, change their electric activity. The donor complexes may appear as per the „sub-threshold“ defect formation mechanism as well [20]. The transformation of the impurity-defect system is amplified by static and dynamic fields of elastic stresses inherent to the Si-SiO_2 system. With such impurities as hydrogen and carbon, the defects typical for the Si-SiO_2 system may become multi-charged, the dissociation energies can change, and these factors can lead to the change of the intensity of the elastic waves occurring under impact of the radiation of the „sub-threshold“ energies. This results in the different relaxation nature of the SOI structures.

The different relaxation nature of the electrophysical parameters is correlated, to a greater extent, to the difference of the hydrogen concentration at the interface of the instrument layer and the dielectric for the structures with the various hydrogen implantation doses. Besides, hydrogen can change the characteristics of diffusion of other impurities, i.e. nitrogen and carbon in this case, which can also change the ratio of the donor and acceptor traps. This conclusion is supported by the fact that the charge relaxation at the substrate interface is the same for the various hydrogen implantation doses, and at the same time the distributions of nitrogen and carbon at the interface of the concealed dielectric and the substrate do not differ, too.

4. Conclusion

A different nature of the relaxation dependence and the time of rebuilding of the electrophysical parameters for the SOI structures with the various hydrogen implantation doses. The structure with the lower hydrogen implantation dose exhibits better results then the structure with the higher dose: the carrier mobilities in the structure #4 are higher, and the charge density at the interface with the instrument layer is lower. The differences of the electrophysical characteristics for the SOI structures with the various hydrogen implantation doses are correlated, to a greater extent, to the hydrogen distribution and the ionization effects than to the structural and morphological disruptions. The electrophysical characteristics are relaxed due to the „sub-threshold“ defect formation mechanisms. The difference of the concentrations of carbon and nitrogen at the Si-SiO_2 interface at the side of the instrument layer also changes the ration of the acceptor and donor traps and, consequently, contributes to the difference of the relaxation of the SOI structures.

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Conflict of interest

The authors declare that they have no conflict of interest.

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