X Международная научная конференция

# «АКТУАЛЬНЫЕ ПРОБЛЕМЫ ФИЗИКИ ТВЕРДОГО ТЕЛА»

X International Scientific Conference
«ACTUAL PROBLEMS OF SOLID STATE PHYSICS»

## СБОРНИК ДОКЛАДОВ

PROCEEDINGS BOOK

# APSSP 2023


ГО "НАУЧНО-ПРАКТИЧЕСКИЙ ЦЕНТР НАЦИОНАЛЬНОЙ АКАДЕМИИ НАУК БЕЛАРУСИ ПО МАТЕРИАЛОВЕДЕНИЮ"

SSPA “Scientific-Practical Materials Research Centre of NAS of Belarus”

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(ИНСТИТУТ ФИЗИКИ ТВЕРДОГО ТЕЛА И ПОЛУПРОВОДНИКОВ)

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В сборнике опубликованы доклады, представленные на Международной научной конференции по актуальным проблемам физики твердого тела. В нем изложены результаты новейших исследований по проблемам физико-химических технологий, функциональных материалов, наноматериалов и нанотехнологии, теории и моделирования в материаловедении. Значительное количество докладов посвящено вопросам практического применения разработанных материалов, технологий и устройств.

Материалы докладов одобрены и рекомендованы к опубликованию организационным комитетом конференции.

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# Actual Problems of Solid State Physics

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The proceedings book contains articles presented at the International Scientific Conference on actual problems of solid-state physics. It presents the current research results on the problems of physical and chemical technologies, functional materials, nanomaterials and nanotechnology, theory and modeling in materials science. A significant number of articles are devoted to the practical applications of the developed materials, technologies, and devices.

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# Impedance of defective silicon layers formed in Al/$SiO_2$/$n$-Si structures by irradiation with high-energy helium ions

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**Abstract**

Al/$SiO_2$/$n$-Si MOS structures irradiated with 5 MeV helium ion are studied. The irradiation fluence varied from $10^{10}$ to $10^{12}$ cm$^{-2}$. The capacitance–voltage (C-V) characteristics, frequency dependences of impedance $Z$ and DLTS spectra were measured. It was found that irradiation leads to an increase in $Z'$ of structures in the depletion mode in the frequency range $f$ = 2–500 kHz. Compensation of doping impurity by radiation-induced defects is accompanied by a decrease in the capacitance of structures in the deep inversion mode. DLTS spectroscopy confirmed that the surface states density increase, caused by helium ion irradiation, affects impedance spectra of the structures.

**Key words:** impedance, MOS structures; silicon; radiation-induced defects; DLTS.

## Introduction

Metal–oxide–semiconductor (MOS) structures are the basic elements of integrated circuits [1]. Irradiation effects leads both to the formation of point radiation-induced defects and their complexes and to the surface states density increase. Each of these factors can lead to performance degradation and failure of semiconductor devices and integrated circuits. C-V measurements is a standard technique for study of MOS structures [2]. However in the case of irradiation with high fluences (especially with heavy ions) an increase in the resistance of silicon due to the compensation of the doping impurity by radiation-induced defects makes the direct use of C-V techniques difficult [3–5]. In this case, additional information can be obtained with application of impedance spectroscopy [6].

In [7] it is reported that changes of C-V characteristics after MOS structures irradiation with helium ions are likely to be due to several reasons. Capture of positive charge (holes) by traps in the oxide layer; increase in the surface states density; radiation-induced defects in the silicon layer adjacent to $SiO_2$; and also formation of a quasi-continuous radiation-damaged layer due to overlapping and merging of radiation-induced defect areas are among those reasons.

The purpose of the paper is to study the effect of radiation-induced defects on the impedance of Al/$SiO_2$/$n$-Si MOS structures irradiated with 5 MeV helium ion.

## Experimental

Al/$SiO_2$/$n$-Si MOS structures were fabricated on (100)-oriented Czochralski-grown silicon wafers. The silicon substrates were of $n$-type (phosphorus-doped) with resistivity of 4.5 Ohm·cm. The silicon dioxide ($SiO_2$) layer of 420 nm thickness was formed by thermal oxidation at 950 °C for 225 min. Electrical contacts to both sides were formed by aluminium sputtering (Al layer thickness was 0.7 μm; area was 1.85×1.85 mm$^2$) with subsequent burning-in at 475 °C in nitrogen atmosphere. The wafers were separated into 2.5×2.5 mm$^2$ chips. Unbiased 5 MeV helium ion irradiation was carried out at room temperature at the accelerator at the Ruhr-University (Bochum, Germany). The irradiation was performed from the Al/$SiO_2$ side for three fluences ($\Phi = 10^{10}$, $10^{11}$ and $10^{12}$ cm$^{-2}$). Mean projective range calculated by the SRIM package was ≈ 24 µm.

The real and imaginary parts of the impedance $Z = Z' + iZ''$ were measured in the frequency range $f$ from 20 Hz to 30 MHz using LCR meters Agilent E4980A and 4284A at the constant bias voltage $U$ ranged from −40 to 40 V. The amplitude of the sinusoidal measuring signal was 40 mV. The values of electrical capacitance of the structures was calculated according to the standard technique [8]. Capacitance-voltage characteristics $C(U)$ were measured in the bias voltage range $U$ from −40 to +40 V with 0.1 V step. All measurements were performed in darkness at room temperature.

DLTS spectra measurements were carried out in the temperature range $T$ = 80–300 K with 1 K step using DLTS spectrometer CE-7C [9]. The frequency of the measuring signal was 1 MHz. The bias voltage during the filling pulse was $U_p$ = –0.5 V, during the emission pulse $U_e$ = –7 V. The duration of the filling pulse was $t_p$ = 0.75 ms, the duration of the emission pulse was $t_e$ = 20 ms. Heating up to the subsequent temperature and its stabilization was carried out with application of potential difference $U_e$ to the structure.

Normalized DLTS spectrum value $S$ was calculated according to the formula:

$$S = [\Delta C(t_2) - \Delta C(t_1)]/C_0, \quad (1)$$

where $\Delta C(t)$ is change of the non-stationary value of the barrier capacitance recorded during the emission pulse; $t_1$ and $t_2$ are some moments of time, with $t_1 < t_2 < t_e$; $C_0$ is the stationary value of the barrier capacitance at the current temperature.

**Results and discussion**

Figure 1a shows $Z'(f)$ characteristics of the MOS structure irradiated with the fluence $\Phi = 10^{12}$ cm$^{-2}$. $Z'(f)$ characteristic depends substantially on whether the structure is in inversion or depletion mode. With $U$ = −25 V (strong inversion mode) there are two inflections at $f \approx 2$ kHz and $f \approx 200$ kHz in the characteristic. The latter is associated with the transition with increasing frequency $f$ of $Z'$ of the structure to the value typical for the $n$-Si substrate. This is confirmed by the similar behavior of $Z'(f)$ characteristics measured in accumulation and in depletion modes. The inflection at ≈2 kHz may be related to the formation of a silicon layer with a high content of radiation-induced defects which compensate the doping impurity. In the frequency range $f$ = 1–200 kHz impedance of the irradiated structure in depletion mode ($U$ = −10 V) exceeds the impedance of the structure in strong inversion mode. The lower values of $Z'$ in the strong inversion mode (compared to the value of $Z'$ in the depletion mode) are observed due to the additional generation of charge carriers on the radiation-induced surface states.

Normalized C-V characteristics shown in Fig. 1b confirm the presence of the radiation-damaged layer. Besides the flat band voltage shift, C-V characteristic behavior changes with the irradiation of the structures. The capacitance of MOS structures in the strong inversion mode decreases with irradiation fluence. It is caused by an increase in the thickness of the space charge region in the $n$-Si substrate due to an increasing doping impurity compensation during irradiation. It should be noted that the capacitance change of irradiated structures with voltage $U$ occurs (compared to the virgin samples) in a wider voltage range, which is related with the influence of surface states and with compensation of silicon.

Figure 2a shows the DLTS spectra of the virgin and irradiated MOS structures. No significant DLTS signals were recorded for the virgin structure. The spectrum of the structures irradiated with helium ions with fluence of $10^{10}$ cm$^{-2}$ is a sloping line without a maximum. For fluence of $10^{11}$ cm$^{-2}$ the DLTS spectrum appears to have a structureless "triangular" shape. The most probable cause of such a spectrum is the emission of electrons from the surface states with distributed in a wide energy range levels [7].

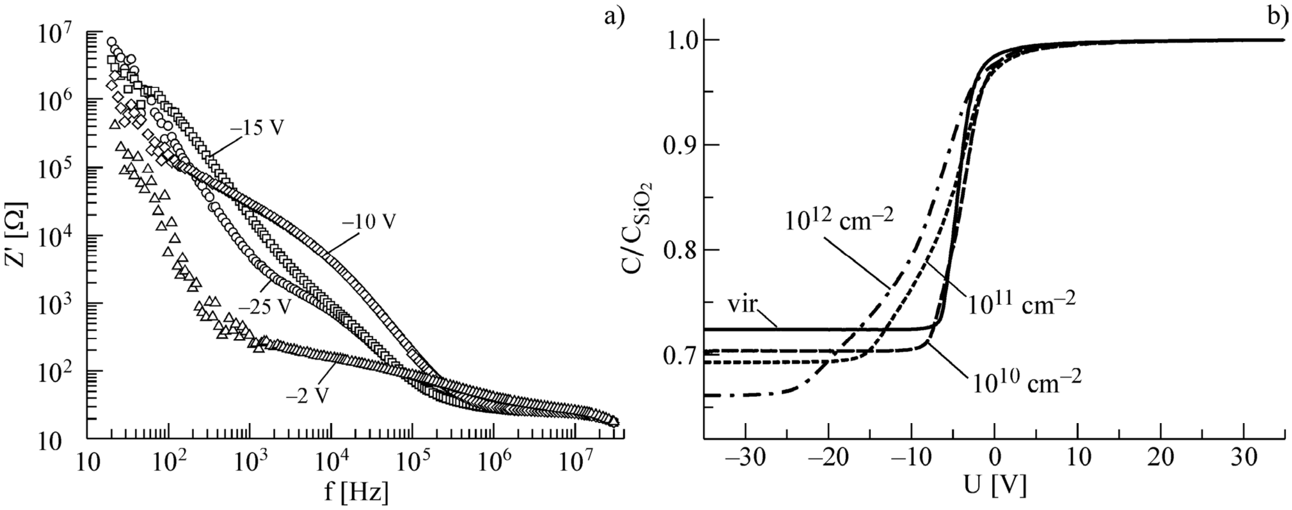


Figure 1. a) Dependence of the real part of the impedance $Z'$ on the AC frequency $f$ for Al/$SiO_2$/$n$-Si MOS structure irradiated with 5 MeV helium ions with fluence of $10^{12}$ cm$^{-2}$. b) C-V characteristics of MOS structures irradiated with helium ions. The constant bias voltage values at which $Z'(f)$ measurements were carried out and the irradiation fluences are shown in the figure. The capacitance values $C$ are normalized to the capacitance of the silicon dioxide layer

For MOS structures irradiated with helium ions with fluence of $10^{12}$ cm$^{-2}$, additional peaks labelled E1, E2, and E3 are observed against the "triangular shape" signal with the E4 peak. The E1–E3 peaks are due to electron emission from deep levels of radiation-induced defects.

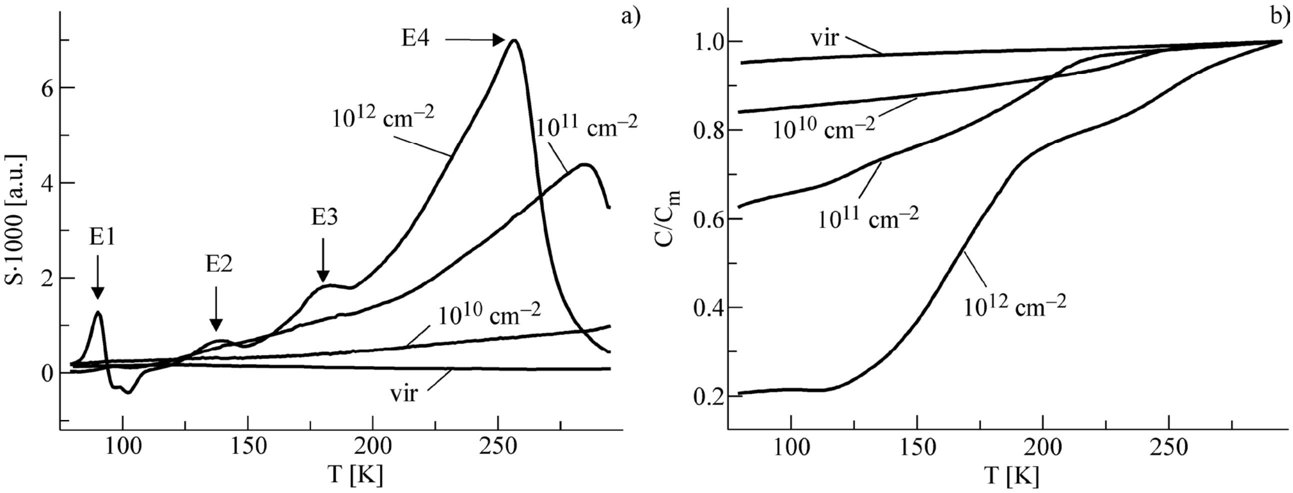


Figure 2. a) DLTS spectra of the virgin (vir) and helium-irradiated structures. b) Dependences of the structure capacitance $C$ on temperature $T$ measured at the bias voltage $U = -7$ V. Irradiation fluences are shown in the figure

From the Arrhenius plot for deep levels the following ionization energies were obtained: E1 peak corresponds to $E_c - 0.16\pm0.01$ eV, E2 — to $E_c - 0.23\pm0.01$ eV, E3 — to $E_c - 0.34\pm0.03$ eV. The activation energies corresponding to E1 and E2 peaks are rather close to the energies of A-center (vacancy-oxygen complex) and divacancy in the charge state (=/−). The E3 peak probably corresponds to the unresolved signal from the (−/0) charge state divacancies and from the vacancy-phosphorus complex.

Figure 2b shows the temperature dependence of capacitance $C$, measured with applied bias voltage $U_e$ = –7 V. The capacitance of the virgin structures weakly depends on the temperature. With increasing irradiation fluence from $10^{10}$ to $10^{12}$ $cm^{-2}$ decreasing of $C$ is manifested more distinctly with decreasing temperature which also confirms the formation of radiation-damaged layer.

**Conclusion**

It is shown that the impedance of the Al/$SiO_2$/$n$-Si MOS structures irradiated with 5 MeV helium ions in the depletion mode in the frequency range 2–500 kHz is formed with the participation of generation and recombination of charge carriers both on the surface states and on the radiation-induced defects. Compensation of doping impurity leads to increase in impedance of the boundary regions of silicon.

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