

RADIATION HARDNESS OF MOS STRUCTURES EXPOSED TO HIGH-ENERGY IONS

MOS structures exposed to 305 MeV Kr and 710 MeV Bi ions irradiation with fluences of 10^9 cm^{-2} and 10^{10} cm^{-2} were investigated by capacitance measuring methods ($C-V$, $C-t$), completed by quasistatic low-frequency $C-V$ and DLTS measurements.

The irradiated MOS structures were functional in spite of a high density of radiation defects. The electric activity of the defects brought a sharp decrease in the generation parameters t_r and τ_g . The parameters of six deep levels were detected in the MOS structures exposed to 710 MeV Bi ions irradiation. Five of these levels with energies 0.52 eV, 0.14 eV, 0.17 eV, 0.25 eV, 0.27 eV were radiation defects.

Keywords: Silicon; high-energy ion implantation; irradiation; MOS structure; capacitance method; DLTS

1. Introduction

Recently there has been a growing interest in the use of high-energy heavy ion irradiation for electronic materials modification [1]. The issues involved in high-energy ion implantation are open both on the fundamental [2] as well as on the applied aspects of the process [3]: the understanding of defect creation and its kinetics on the one hand, and the application of deep implantation on the other hand.

This study is also very useful for knowledge of the radiation hardness of electronic devices in a high radiation environment in a reactor laboratory or in the outer space.

The scope of this paper is to investigate the effect of the 305 MeV Kr and 710 MeV Bi ion irradiation on the electrical properties of MOS structures.

We used the capacitance-voltage $C-V$ method to determine the flat-band voltage U_{FB} and the free carriers concentration profile $n(x)$ in the structures before and after irradiation. The kinetics of the generation process that takes place in the space charge region was diagnosed by the non-equilibrium $C-t$ method [4]. Parameters obtained from this method, the relaxation time t_r , the generation lifetime of minority charge carriers τ_g and the surface generation velocity S_g characterize the electrical behaviour of defects in the MOS structure.

The energy distribution of the insulator-semiconductor interface trap density D_{it} was obtained from the low frequency $C-V$ curve. We used the quasistatic charge-voltage method [5].

In particular, deep level transient spectroscopy (DLTS) [6] proved to be highly applicable because of its good sensitivity, and specific defect centers with well-defined signatures can be moni-

tored to concentrations of $\sim 10^{-5}$ below the dopant concentration. We used the standard capacitance DLTS method with electrical excitation.

2. Experiment

An n -type Czochralski-grown antimony doped (100)-oriented homogeneous wafer of silicon with resistivity 2–5 Ωcm and thickness 300 μm was used as a substrate of the MOS structure. The gate SiO_2 layers were prepared by thermal oxidation in the atmosphere of dry oxygen at 1050 $^\circ\text{C}$ for 90 minutes. The thickness of the SiO_2 layer was about 100 nm. All gates were vapour deposited and patterned photolithographically. After manufacturing the MOS structures, the sample was annealed in $\text{N}_2 + \text{H}_2$ at 460 $^\circ\text{C}$ for 20 minutes. The ohmic contact from the backside of the wafer was prepared by vapour deposition of Al.

Afterwards, the MOS structures were exposed to 305 MeV Kr ion irradiation with a fluence of 10^9 cm^{-2} (samples D1) and a fluence of 10^{10} cm^{-2} (samples D2) and to 710 MeV Bi ion irradiation with a fluence of 10^9 cm^{-2} (samples D8) and with a fluence of 10^{10} cm^{-2} (samples D6) at the Joint Institute for Nuclear Research in Dubna, Russia [7].

The non-irradiated MOS structure (D0) and the irradiated MOS structures (D1, D2, D6, D8) were characterized by $C-V$, low-frequency $C-V$ and $C-t$ methods. High frequency capacitance-voltage $C-V$ and non-equilibrium capacitance-time $C-t$ measurements were performed using the 4280 1 MHz C Meter/ $C-V$ Plotter Hewlett-Packard [8]. Quasistatic low frequency $C-V$ measurements were performed using the Keithley 595 Quasistatic CV Meter. The MOS structures (D0) and irradiated (D6, D8) were also investigated by a standard DLTS method. This method is a high-frequency transient capacitance thermal scanning method, where the capac-

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itance transient effect in the potential barrier of a semiconductor is caused by an electrical excitation pulse. DLTS measurements were performed using a BioRad boxcar detection system.

3. Results and Discussion

The MOS structures (sample D0) used in this experiment were of high quality, having a low density of defects. This presumption was verified by many measured DLTS spectra under different measuring conditions (Fig. 1).

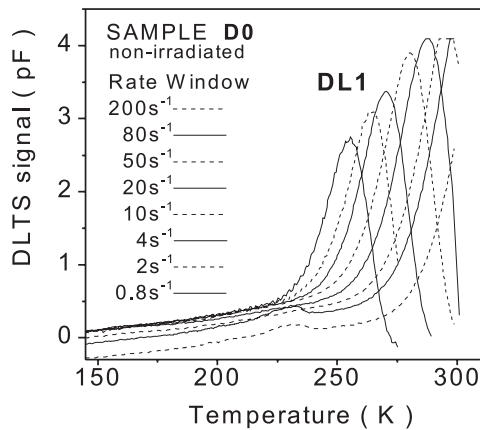


Fig. 1. Typical measured DLTS spectra of the sample D0 at optimal measuring conditions ($U_R = -1$ V, $U_F = -0.25$ V, $t_F = 0.8$ ms). DL1 is the determined energy deep level.

We found only one deep level DL1 (0.61 eV) with a very low concentration of 2×10^{13} cm⁻³. This deep level corresponds to the presence of Au (0.59 eV) [9].

In $C-V$ measured curves (Fig. 2), we observed a rise in the positive defect charge in the oxide and at the interface with the silicon substrate, which resulted in an increased flat band voltage (Tab. 1).

The antimony doped MOS structures had the same or only slightly lower concentration of impurities, N_D , after irradiation with

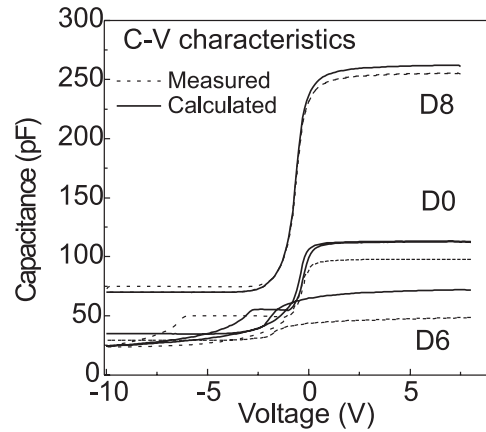


Fig. 2. MOS structures D0, D6, D8 measured and calculated $C-V$ curves; the calculated $C-V$ curves include a correction for the effect of conductance upon the measurement of the capacitance.

Kr and Bi ions. Significant changes in the parameters of the MOS structure were observed in the non-equilibrium state. In $C-t$ measurements we observed a marked decrease of the relaxation time, t_r , see Fig. 3.

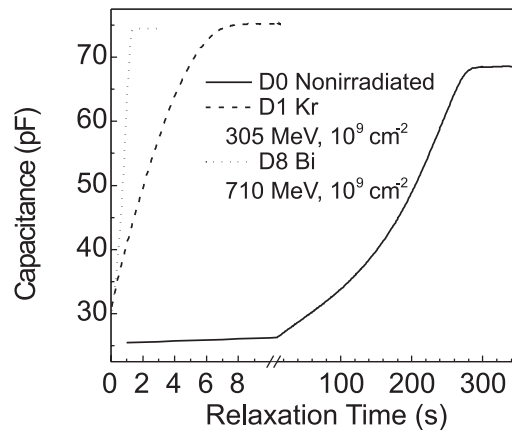


Fig. 3. MOS structures D0, D1, D8 measured $C-t$ curves of MOS structure before and after irradiation by Kr and Bi ions with the same fluence 10^9 cm⁻²

Parameters extracted from $C-V$, low-frequency $C-V$ and $C-t$ measurements on MOS structures. The values of D_{it} were determined for the level 0.22 eV above the midgap (Fig. 6).

Tab. 1

Sample	U_{FB} (V)	N_D (m ⁻³)	t_r (s)	τ_g (μ s)	S_g (ms ⁻¹)	D_{it} (m ⁻² eV ⁻¹)
D0 - nonirradiated	-0.1	1.22×10^{21}	487	472	2.2×10^{-3}	9.1×10^{14}
D1 - Kr, 305 MeV, 10^9 cm ⁻²	-0.4	1.1×10^{21}	10	3.9	3.1×10^{-3}	2.4×10^{15}
D2 - Kr, 305 MeV, 10^{10} cm ⁻²	-1.2	0.98×10^{21}	1.9	0.8	1.3×10^{-1}	1.3×10^{16}
D8 - Bi, 710 MeV, 10^9 cm ⁻²	-0.5	1.1×10^{21}	1.7	1.3	4.5×10^{-1}	1.86×10^{16}
D6 - Bi, 710 MeV, 10^{10} cm ⁻²	no $C-V$	-	no $C-t$	-	-	no If $C-V$

The rise in the density of radiation defects is expressed quantitatively through parameters τ_g and S_g (Tab. 1). The highest density of electrically active defects was found in the case of Bi ions with higher energies than those of Kr. Remarkable differences in the generation parameters were observed also in dependence on the fluence of irradiation. In Fig. 4 one can see the shortening of the time of relaxation after irradiation by Kr ions with a higher fluence.

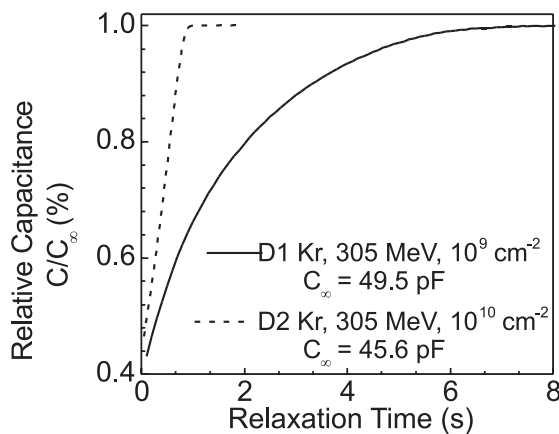


Fig. 4. MOS structures D1 and D2 measured C-t curves of MOS structure after Kr ion irradiation with fluences 10^9 cm^{-2} and 10^{10} cm^{-2} .

In the case of irradiating with ions of Bi with a fluence of 10^{10} cm^{-2} a significant increase in the conductivity of the insulating layer was observed (Fig. 5).

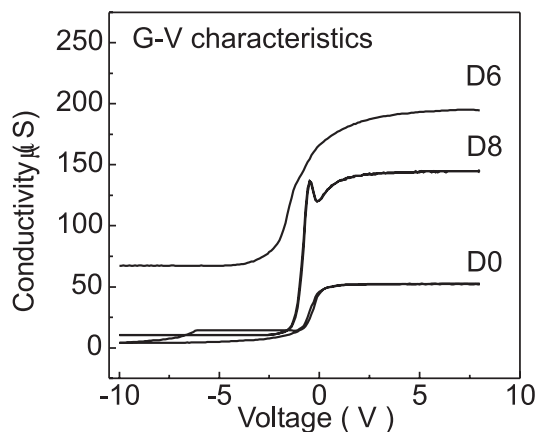


Fig. 5. MOS structures D0, D6, D8 measured G-V curves - conductivity from applied voltage.

C-V measurements and the calculation of D_{it} (Fig. 6) reveal that the growing dose and energy of implanted ions increase the density, D_{it} . A similar trend can be observed also in the change of

the surface generation velocity, S_g . One can deduce that the quality of the Si - SiO₂ deteriorates. In spite of that the irradiated MOS structures still remain their capacitance properties and functionality.

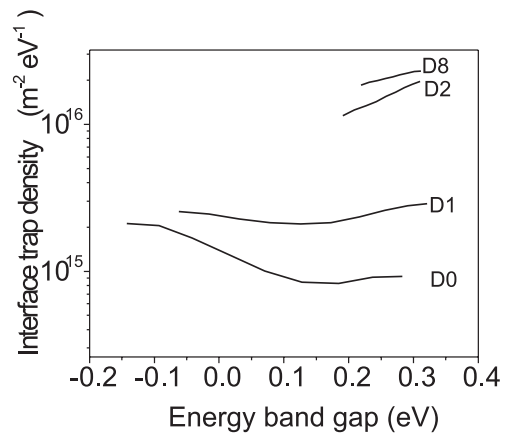


Fig. 6. The energy distribution of the Si-SiO₂ interface trap density. D0 - nonirradiated, D1 - Kr, 305 MeV, 10^9 cm^{-2} , D2 - Kr, 305 MeV, 10^{10} cm^{-2} and D8 - Bi, 710 MeV, 10^9 cm^{-2} .

The measured DLTS spectra of the MOS structures after Bi ion irradiation with fluences 10^9 cm^{-2} and 10^{10} cm^{-2} (D6 and D8) exhibit a strong deviation from an exponential dependence (Fig. 7).

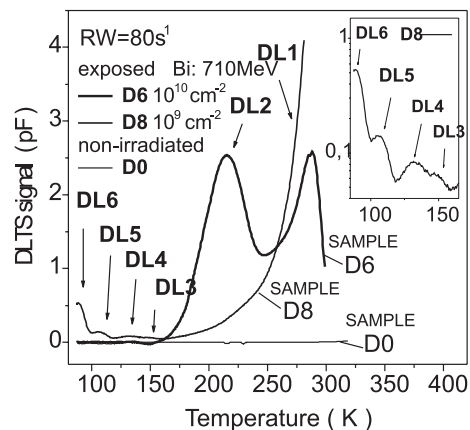


Fig. 7. Typical measured DLTS spectra of the samples D0, D6, D8 for rate window 80 s^{-1} at the same measuring conditions (reverse voltage $U_R = -3 \text{ V}$, filling pulse $U_F = -1.1 \text{ V}$, and pulse time $t_F = 0.8 \text{ ms}$). DL1-DL6 are the determined energy deep levels.

This can be caused by the presence of several mutually influencing deep energy levels. Six peaks labelled DL1, DL2, DL3, DL4, DL5 and DL6 were detected. These deep levels DL1-DL6 are traps of majority charge carriers (electrons). The values of the activation enthalpies (E_n of electron deep levels and the capture

Parameters of the measured deep levels extracted from the Arrhenius diagram.

Tab. 2

Deep Levels	activation enthalpies ΔE_n (eV)	cross section σ_n (cm ⁻²)	concentration (cm ⁻³)			Temperature at RW = 100 s ⁻¹	Similar traps in literature
			sample D0	sample D6	sample D8		
DL1	0.611	1.8×10^{-15}	2×10^{13}	3×10^{15}	1×10^{15}	305.4	Au, 0.59eV [8]
DL2	0.523	1.9×10^{-13}	no detect	1×10^{15}	4×10^{14}	223.0	E - centre [8]
DL3	0.269	2.9×10^{-16}	no detect	no detect	7×10^{13}	152.1	V ⁻² [9]
DL4	0.246	1.2×10^{-16}	no detect	no detect	9×10^{13}	134.2	V ⁻² [9]
DL5	0.171	1.3×10^{-15}	no detect	no detect	2×10^{14}	107.8	A - centre [8]
DL6	0.143	4.9×10^{-16}	no detect	no detect	7×10^{14}	88.1	A - centre [8]

cross section for electrons σ_n were determined from the Arrhenius diagram using the known equations [6] (they are listed in Tab. 2).

In principle it was shown, see Fig. 7, that the deep energy deep DL1 was found in all the three investigated samples D0, D6, D8, while the deep energy level DL2 can be detected only in the structures irradiated by Bi ions. We can suppose that it was a radiation defect with an activation enthalpy of 0.52 eV, which probably corresponds to an E - centre (vacancy-phosphorous) in irradiated Si [9]. This deep level dominates in structure D6.

DL3, DL4, DL5 and DL6 peaks were detected only in D8 structures irradiated by Bi ions with fluency 10^9 cm⁻². These are radiation defects. We suppose that DL3 (0.27 eV) and DL4 (0.25 eV) deep level are divacancies V⁻² in Si [10] created by the implantation process and DL5 (0.17 eV) and DL6 (0.14 eV) correspond probably to the A - centre (vacancy-oxygen) in irradiated Si [11].

4. Conclusion

From the capacitance C-V and C-t measurements we found that MOS structures irradiated by high energies and doses of Kr

and Bi ions were functional in spite of a high density of radiation defects. In the case of Bi ions with a higher energy than that of Kr ions, the conductivity of the insulating layer increased. We did not observe a decrease in the concentration of shallow impurities in irradiated MOS structures. The radiation defects created at the Si-SiO₂ interface increased the trap density and their electrical activity.

We detected six deep levels in MOS structures irradiated by Bi ions with energy 710 MeV and fluency 10^9 and 10^{10} cm⁻². Five of them, DL2-DL6, were produced by radiation. DL3-DL6 levels cannot be detected under higher fluency (10^{10} cm⁻²). Our interpretation of this fact is following: irradiation with a fluency of 10^{10} cm⁻² caused gettering of DL3-DL6 defects. This fluency also causes great oxide layer damage. At the same time, the concentration of DL2 defect in structure D6 rose strongly.

Acknowledgements

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