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Changes in Si-SiO_2 structure characteristics generated by MeV electron irradiation♣

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We report on the influence of MeV electron radiation on the electronic characteristics and mechanical stress of Si-SiO_2 structures. n-type Si wafers were oxidized at 1050 °C in dry oxygen to produce 10 nm thick oxide layers. Samples were then irradiated by 23 MeV electrons with doses varying from $2.4\text{x}10^{14}$ to $2.5\text{x}10^{16}$ el.cm^{-2}. The radius of curvature was measured before and after the irradiation dose. Quasi-static Capacitance-Voltage and Thermally-Stimulated Current methods were used to study the electronic defect characteristics of the corresponding MOS structures. It was found that radiation defects induced at the Si-SiO_2 interface and in the oxide correlated with measured stress changes, in a manner that depended on the irradiation dose.

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1. Introduction

The use of MIS (metal-insulator-semiconductor) structures, such as MOS transistors, integrated circuits and charge coupled devices in modern technology extends over a wide range of operating conditions and environments. Thus in addition to the scientific interest, a study of the correlation between the electronic and mechanical properties of MIS structures under different external conditions is also of commercial relevance.

Recently, the influence of MeV electron irradiation on MOS characteristics has been intensively studied [1-3]. Previously, we studied the influence of high-energy electron irradiation induced defects on the mechanical properties of thermally grown SiO_2 on n-and p-type Si substrates [4]. It was proposed that the curvature change patterns for n- and p-type Si-SiO_2 structures are associated with defects created at the Si-SiO_2 interface. An increase in the nano-hardness with electron irradiation dose was also observed, and was proposed to be a result of a reduced positive charge in the oxide. The variation in the mechanical properties of n- and p-Si-SiO_2 structures, caused by MeV electron irradiation, depended on the dopants in the silicon substrates.

The aim of the present work is to compare the influence of MeV electron radiation on both the electronic (carrier traps) and mechanical (strain) properties of Si-SiO_2 structures. Quasi-static Current-Voltage (C-V), Thermally-Stimulated Current (TSC) and Newton's rings methods were used for this purpose. It is shown that the density of defects created at the Si-SiO_2 interface and in the oxide correlates with mechanical stress changes.

2. Experimental

In this study, n-Si substrates of <100> orientation were used. Wafers of 4.6 Ω.cm resistivity were oxidized at 1050 °C in a flow of dry oxygen, in order to produce a 10 nm thick oxide, as measured by ellipsometry. After oxidation, the samples were cooled at a rate of 1 °C/s in oxygen ambient (the same ambient in which the oxidation was carried out).

The radius of curvature of each Si-SiO_2 structure was then measured using the Newton's rings method with an adapted microscope [5]. With this technique, it was possible to determine not only the magnitude but also the bending direction of the Si-SiO_2 structures and hence distinguish between compressive and tensile stress. The error in the curvature determination was different for each sample and thus for simplicity the highest error of 10% is taken as representative in all cases.

A series of Si-SiO_2 samples was irradiated by 23 MeV electrons from a Microtron MT-25, at the Flerov Laboratory of Nuclear Reactions of the Joint Institute of Nuclear Research (FLNR, JINR) Dubna, Russia. The beam current during irradiation was about 7 μA. After irradiation with doses of $2.40\text{x}10^{14}$, $4.80\text{x}10^{14}$, $2.40\text{x}10^{15}$,

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4.80x10^{15}, 1.24x10^{16}, 2.48x10^{16} el.cm^{-2}, the radius of curvature of each Si-SiO$_2$ sample was again measured.

The samples were then prepared for electronic measurements. Al gate electrodes were deposited by sputtering and defined by photolithography, and ohmic contacts formed on the back side of the wafer. A number of un-irradiated samples were also prepared, for reference. The radiation dose dependence of the energy profile of MOS interface state density was then measured using C-V and TSC.

3. Results and discussion

The multilayer character of the MOS structure reduces to residual strains and mechanical stresses of the oxide. Radiation defects induced by MeV energy electron irradiation during the whole structure also contribute to the residual strains and mechanical stresses of the oxide. The mechanical stress of Si-SiO$_2$ structures is compared to the radiation induced defects at the Si-SiO$_2$ interface and in the oxide of the corresponding MOS structures, as can be seen in Table 1. It has to be noted that ohmic contact deposition leads to compressive stress in the Si substrate [6]. The first electron irradiation dose applied (2.40x10^{14} el.cm^{-2}) and interface state density, respectively, are not yet enough to significantly change the substrate bending, and the curvature sign is still negative. As the dose increases in the range of 4.80x10^{14} - 4.80x10^{15} el.cm^{-2}, a stress transition is observed as a result of about a twofold increase in the interface state density. Since MeV electron irradiation penetrates through the whole Si-SiO$_2$ structure and breaks Si-O bonds at the interface, such a state is not thermodynamically stable. The latter, in its turn, is reflected in the deformation energy, which defines the macroscopic elastic parameters of the structure. In this range of doses, the density of the radiation defects in the bulk oxide is negligible, as will be discussed in more detail below.

Table 1. Correlation between total interface state density and mechanical stress of Si-SiO$_2$ structures irradiated with different doses of MeV electrons

Dose (el.cm^{-2})	Mechanical stress (GPa)	Total interface state density (x10^{12}cm^{-2})
2.40x10^{14}	- 0.62	18
4.80x10^{14}	+ 23.90	22
2.40x10^{15}	+ 2.20	33
4.80x10^{15}	+ 3.50	41
1.24x10^{16}	- 0.31	43
2.48x10^{16}	- 8.66	42

TSC spectra of MOS structures, with an oxide thickness of 10 nm, after electron irradiation with the doses given in Table 1 reveal four peaks [7, 8]. They correspond to four kinds of energy state located at the Si–SiO$_2$ interface [9]. The parameters of the interface states created by electron irradiation are determined by the initial rise plot and Grossweiner's methods [10]. These interface states are associated with four discrete energy states in the Si band gap. The activation energy of traps corresponding to these interface states is evaluated by the use of the previously mentioned two methods. The coincidence between these two is very good, and the energy values are as follows: $E_c - 0.21$ eV, $E_c - 0.26$ eV, $E_c - 0.32$ eV and $E_c - 0.46$ eV. The calculation of the activation energy of these traps and the cross section of the electron capture allow one to evaluate the nature of the defects [11]. It is well known that the density of radiation induced traps can be determined from the area enclosed by the corresponding peaks [12, 13].

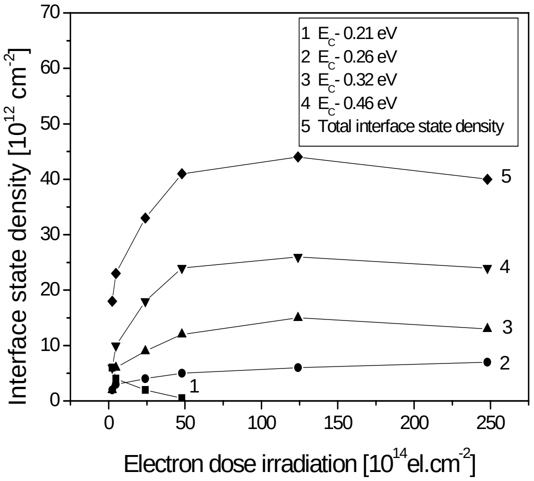

Fig. 1. Interface state density of defects generated at Si-SiO$_2$ interface by MeV electrons.

Fig. 1 presents the interface state density of each kind of defect generated at the Si–SiO$_2$ interface, depending on the electron irradiation dose. A decrease in the density of the $E_c - 0.21$ eV defects detected by the TSC spectra with increasing dose is observed (curve 1). This shows that the density of the shallow level ($E_c - 0.21$ eV) associated with a defect (like the acceptor level of di-vacancies) decreases during irradiation. The density of the defects presented by the higher temperature TSC peaks (corresponding to the deeper levels in the Si forbidden gap ($E_c - 0.26$ eV, $E_c - 0.32$ eV and $E_c - 0.46$ eV) increases with electron dose (curves 2-4) up to a dose of 1.24x10^{16} el.cm^{-2} [14]. The last peak in the spectra corresponding to the level $E_c - 0.46$ eV is associated with defects like vacancy impurity complexes [11]. It should be noted that these (in our case vacancy-phosphorus) are the major kind of defects created by MeV electrons in silicon MOS structures [8]. The total interface state density is given by curve 5. Saturation is observed for irradiation doses higher than 10^{16} el.cm^{-2}.

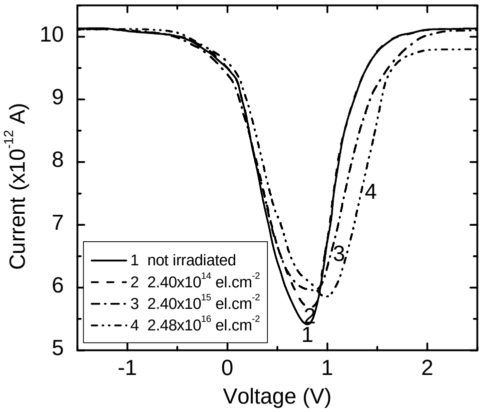

Fig. 2. Quasi-static C/V curves of MOS structures irradiated by 23-MeV electrons with doses of 2.40x10^{14}, 2.40x10^{15}, 2.40x10^{16} el.cm^{-2} (curves 2, 3, 4), respectively.

Fig. 2 shows the normalized quasi-static C-V curves of MOS structures. The initial curve 1 corresponds to a reference (not irradiated) MOS structure. The value of the ratio $C_{min} : C_{ox}$ is low, which signifies a low state density at the Si-SiO$_2$ interface [15]. Quasi-static C-V curves of the samples irradiated by 23 MeV electrons with different doses - 2.40x10^{14}, 2.40x10^{15} and 2.48x10^{16} el.cm^{-2} are presented in curves 2, 3 and 4 respectively. Electron irradiation with a flux of about 10^{14} electrons.cm^{-2} (curve 2) causes a change in C_{min}: C_{ox}, but does not cause any essential shift of the C-V characteristic. This result suggests that an electron irradiation dose of this order introduces interface state defects at the Si-SiO$_2$ interface, but does not change the density of defects in the oxide film. Curve 3 is distorted and the value of C_{min}: C_{ox} increases. This suggests that the density of the radiation-induced interface states increases. The behaviour of the quasi-static *C/V* curves indicates that total interface state density at the Si-SiO$_2$ interface increases. Measurement of the MOS structure irradiated with a dose of 2.48x10^{16} el.cm^{-2} shows that the curve extends and shifts to the right (curve 4). A decrease in C_{min}: C_{ox} is also observed. This may be connected with a decrease in the total radiation defect density, as shown in curve 5 of Fig 1. The shift to the right also means that the positive charge in the oxide film decreases (curve 4). It is possible that radiation defects produced in the oxide by high energy electrons neutralize the existing positive oxide charge.

A comparison of the radiation defect characteristics measured by TSC and C-V methods leads to the following inferences. The electronic properties of MOS structures under electron irrradiation undergo distinctive changes that may involve a modification of the Si-SiO$_2$ interface trap density or the SiO$_2$ bulk defect density, depending on the electron dose. The mechanical stress changes during irradiation of Si-SiO$_2$ structures are correlated with the radiation defects created at the Si-SiO$_2$ interface and in the oxide bulk. The mechanical stress is known to be compressive in thermally grown SiO$_2$ at 1050 °C [6]. The effects on mechanical stress of both processes on interface states and oxide charges generation are difficult to separate. The observed stress transition from compressive to tensile at low doses could be attributed to the interface state generation. A further accumulation of the radiation defects and a higher number of broken Si-O bonds at the Si-SiO$_2$ interface explain the maintainence of a tensile stress. At the beginning of the saturation of the interface state density, a stress transition again appears. Both processes of defect generation, interface states and oxide charges, are in competition. When the second process dominates, the value of the positive charge in the oxide decreases. In this region, the stress behaviour could be associated with the radiation defects created in the oxide bulk only, since the typical compressive stress is about one order higher than that at a dose of 2.40x10^{14} el.cm^{-2}.

4. Conclusions

High energy electron irradiation generates changes in the magnitude and direction of strain in Si-SiO$_2$ structures, which can be attributed to the radiation induced defects at the Si-SiO$_2$ interface and in the oxide. Both kinds of defect influence the electrical and mechanical characteristics of the structures. At lower doses of MeV electron irradiation, a primary role in the mechanical stress changes is assigned to the radiation induced interface states, whereas at higher doses (> 10^{16} el.cm^{-2}) the oxide charge predominates.

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