MeV electron irradiation of Si-SiO$_2$ structures with magnetron sputtered oxide

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Abstract. MeV electrons influence on the characteristics of Si-SiO$_2$ structure with magnetron sputtered oxide was studied by ellipsometry and the thermally stimulated current (TSC) method. The MOS structures used in this study were fabricated on $<100>$ oriented p-Si wafers of 12.75 - 17.25 Ω.cm resistivity. Magnetron sputtered oxides with different thicknesses of 20 and 100 nm were deposited on p-Si substrates. Both groups of samples were irradiated by 23 MeV electrons. The oxide thicknesses and TSC characteristics of the MOS samples were measured before and after MeV electron irradiation with doses of 4.8×10$^{15}$ and 4.8×10$^{16}$ el.cm$^{-2}$. The oxide thicknesses of both groups of samples increased after irradiation. The main defects generated by the MeV electrons were evaluated. It was shown that the trap concentration increases with the electron irradiation dose. The main peak in the TSC characteristics gives information about the main radiation defects at the Si-SiO$_2$ interface of the MOS structures. These defects can be related to the vacancy-boron complexes which are associated with the main impurities in the p-Si substrate. These results correspond to our results reported earlier for MeV electron irradiated Si-SiO$_2$ structures with thermally grown oxide. But (in this case) the effects observed are more pronounced for the magnetron sputtered oxide. A possible reason is the higher defect concentration generated in the magnetron sputtered oxide during its deposition on Si-substrates.

1. Introduction

The silicon MOS structure is the basis of electronic and microelectronic devices, although novel configurations and compositions are constantly being introduced. The long-term application of Si-SiO$_2$ structures in the modern semiconductor device industry is based on the fact that an extremely stable Si-SiO$_2$ interface with a low interface state density can be achieved. It is well known that the Si-SiO$_2$ interface is the part of the MOS structures that is most sensitive to different kinds of irradiation. One solution of the problem of reducing the radiation effects on the MOS structure is to modify the oxide materials in such a way as the required parameter can be achieved. We report on a study of MOS structures characteristics with magnetron sputtered SiO$_2$ before and after MeV electron irradiation.
MeV electron irradiation is a very useful tool for studying the operation of MOS devices in a radiation environment. The MeV electrons penetrate through the entire MOS structures, their energy being sufficient to produce hard radiation defects in the whole system: metal, oxide, Si-SiO\textsubscript{2} interface and silicon substrate. Our earlier studies showed that MeV electrons increase the thermally grown oxide thickness of MOS structures [1]. The phase analysis of n- and p-type SiO\textsubscript{2}/Si samples irradiated by MeV electrons carried out by soft X-ray emission spectroscopy have shown that the effect of radiation-stimulated oxidation depends on the type of Si substrate. The increase of the SiO\textsubscript{2} contribution to the spectra is more pronounced for the specimens prepared on n-type silicon wafers. This means that MeV electron irradiation leads to the oxidation of the Si/SiO\textsubscript{2} samples, and this oxidation effect for the thermally grown oxide is more prominent for the samples prepared on n-Si substrates [2].

We present a study on MeV electrons irradiation effect on the characteristics of p-Si-SiO\textsubscript{2} structures with magnetron sputtered SiO\textsubscript{2}. The reactive magnetron sputtering relies on the principle of compound formation by a chemical reaction between the sputtered material, a metal, and a reactive gas added to the sputtering gas, generally Ar [3]. Magnetron sputtering is a quite difficult process to control, mainly because during the deposition the reactive gas reacts not only with the material sputtered to form the compound on the substrate (or on the walls) but also with the target surface [4]. The deposition rate of dielectric compounds is an important parameter, whose control is essential in what concerns the characteristics of the deposited layer [5-6].

In the present work the characteristics of p-Si-SiO\textsubscript{2} structure with magnetron sputtered oxide are studied by ellipsometry and the thermally stimulated current technique before and after different doses of 23 MeV electron irradiation. The oxide thickness and the electrical properties of the Si-SiO\textsubscript{2} structure were investigated as a function of the MeV electron dose irradiation.

2. Experimental details

In this experiment, 12.75 - 17.25 Ω cm p-type <100> oriented single-crystal Si wafers were used to prepare Si-SiO\textsubscript{2} structures. The oxide was deposited on Si wafers by radio frequency magnetron sputtering using a 13.56 MHz planar Leybold-Heraeus system. The deposition was carried out in argon atmosphere at a pressure of 1 Pa and a cathode voltage of 2.0 kV. The oxide thickness of each sample was determined by ellipsometry. The Si-SiO\textsubscript{2} samples were divided into two groups after the oxide deposition - with oxide thicknesses of 20 nm and of 100 nm. Al gate electrodes were photolithographically formed onto the oxide of some of these samples so that MOS capacitors (with oxide thicknesses of 20 and 100 nm) were produced. The Si-SiO\textsubscript{2} and MOS samples were irradiated by 23 MeV electrons produced by a Microtron MT-25 installation at the Flerov Laboratory of Nuclear Reactions of the Joint Institute for Nuclear Research (FLNR, JINR) Dubna, Russia. The beam current during irradiation was about 9 μA. The MeV electrons’ effect on the oxide thickness of the Si-SiO\textsubscript{2} structures and the thermally stimulated current characteristics of the MOS structures were evaluated after two doses (4.8×10\textsuperscript{15} and 4.8×10\textsuperscript{16} el cm\textsuperscript{-2}) of high-energy electron irradiation.

3. Results and discussion

We measured the oxide thickness of non-irradiated and 23-MeV electron-irradiated Si-SiO\textsubscript{2} structures covered by with 20-nm and 100-nm thick magnetron sputtered oxides studied. The oxide thickness changes as the electron irradiation dose was raised were measured by ellipsometry. We found that the oxide film thickness of both groups of the samples increased after irradiation. Table 1 presents the oxide thickness of the Si-SiO2 structures with magnetron sputtered SiO\textsubscript{2} before and after the doses of 23 MeV electron irradiation. It is seen that the oxide thickness increases slowly. The oxide increase for the Si-SiO\textsubscript{2} structures with the thinner film (20 nm oxide) was 2 nm (a value within the experimental error). The oxide thickness of the structures with a thicker (100 nm) magnetron sputtered oxide film increased more pronouncedly after electron irradiation. This could be connected with a higher defect concentration (in the thicker oxide) generated during the magnetron sputtering deposition. We assume that radiation-stimulated oxidation takes also place as a result of the high-energy electron irradiation.
The radiation-stimulated oxidation was more effective in the case of MeV-electron-irradiated p-type Si-SiO\textsubscript{2} structures covered with magnetron-sputtered oxide. The thickness of thermally-grown oxide on p-type Si-SiO\textsubscript{2} structures remained the same after MeV electron irradiation [7, 8].

**Table 1.** Oxide thickness before and after electron irradiation.

| SiO\textsubscript{2} oxide thickness [nm] | Energy 23 MeV, electron irradiation dose [el.cm\textsuperscript{-2}] |
|-----------------------------------------|---------------------------------------------------------------|
|                                         | 4.8×10\textsuperscript{15} | 4.8×10\textsuperscript{16} |
| 20                                      | 22                             | 24                 |
| 100                                     | 112                            | 125                |

The MOS samples were studied using the thermally stimulated current (TSC) technique before and after irradiation by the two doses of MeV electrons.

Figures 1-2 show typical TSC spectra of p-type MOS structures with magnetron-sputtered silicon dioxide of a thickness of 20 nm and 100 nm before and after irradiation by 23 MeV electrons. The MeV electrons create different kinds of defects in the Si-SiO\textsubscript{2} structures (which depend on the oxide thickness) with concentrations depending on the irradiation dose. The thermo-stimulated current is shown as a function of the sample temperature during the measurement for the two electron doses (curves 1 and 2). The TSC spectra obtained of the irradiated samples were composed of several overlapping peaks, so that a thermal and differential field “cleaning” of the spectra were applied to reveal the main peaks [9, 10].

No TSC characteristics of the p-type MOS structures with magnetron-sputtered oxide thickness of 20 nm could be registered before electron irradiation. Figure 1 presents TSC curves after 23 MeV electron irradiation of the MOS samples with doses of 4.8×10\textsuperscript{15} and 4.8×10\textsuperscript{16} el cm\textsuperscript{-2} (curves 1 and 2), respectively. It is seen that the 23 MeV electrons create new states at the Si-SiO\textsubscript{2} interface, i.e., the high-energy electron irradiation creates new discrete energy levels in the silicon forbidden gap. MeV electrons create several kinds of defects at the Si-SiO\textsubscript{2} interface whose concentration increases as the irradiation dose is increased.

Figure 2 presents TSC characteristics of p-type MOS structures with 100-nm magnetron-sputtered oxide thickness – before (curve 0) and after (curves 1 and 2) 23 MeV electron irradiation. Curve 0

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**Figure 1.** TSC curves of p-type MOS structures with 20 nm magnetron sputtered oxide thickness after 23 MeV electron irradiation with doses of 4.8×10\textsuperscript{15} and 4.8×10\textsuperscript{16} el cm\textsuperscript{-2} (curves 1 and 2) respectively.

**Figure 2.** TSC characteristics of p-type MOS structures with 100 nm magnetron sputtered oxide thickness – before (curve 0) and after 23 MeV electron irradiation with doses of 4.8×10\textsuperscript{15} and 4.8×10\textsuperscript{16} el cm\textsuperscript{-2} (curves 1 and 2) respectively.
demonstrates that the radiation defects are created at the Si-SiO\textsubscript{2} interface of the thicker magnetron-sputtered oxide before MeV electron irradiation. This could be connected with the higher defect concentration generated in the magnetron-sputtered oxide during its deposition. It is seen that the irradiation by MeV electrons leads to an increase in the concentration of defects generated in the magnetron-sputtered oxide and, obviously, high energy electron irradiation introduces new radiation defects in the MOS structures. Curve 1 shows an increase in the height and in the areas enclosed by TSC curve after MeV electron irradiation. This is an indication of an increase in the density of all kinds of radiation defects induced in the oxide during its preparation. A further increase in the irradiation dose furthers this tendency, as it is shown by curve 2.

We used two techniques to obtain the activation energy of the traps - the initial rise plot method and the Grossweiner’ techniques were applied to the TSC curves of the two MOS structures (with 20 nm and 100 nm thick oxide). The last peak of the TSC curves (in figure 1 and figure 2) is attributed to the level with energy position $E_v = +0.45$ eV and is associated with boron-vacancy complex defects. The generation of this kind of defects increases as the boron concentration in the Si substrate is increased, and, in contrast, the generation decreases as the oxygen concentration in the Si wafer is increased [11]. Curves 1 and 2 in both figures also confirm the fact that the main defects created by the high-energy electron irradiation correspond to the V-B defects and their concentration increase with the increasing of the irradiation dose. The area enclosed by the higher temperature peaks increases effectively with the increase of the electron dose. These results correspond to our earlier studies that showed that most of the radiation defects induced by high-energy electrons at the Si-SiO\textsubscript{2} interface of MOS structures (with thermally grown oxide) have to do with the main impurities in the Si substrate [6,7]. This result can be explained by taking into account that the high-energy electron irradiation generates vacancies, which tend to form complexes with the basic impurities of the substrate (such as boron in p-type Si wafers).

We, therefore, assume that the higher defects concentration generated in the magnetron-sputtered oxide during its deposition creates conditions for a higher degree of defects concentration following the MeV electrons irradiation.

4. Conclusions
The oxide thickness of Si-SiO\textsubscript{2} and MOS structures with magnetron-sputtered oxide deposited on p-type Si substrates increases after irradiation by different doses of 23 MeV electrons. The thickness of structures with a thicker (100 nm) magnetron-sputtered oxide film increases to a larger extent after electron irradiation. Our results also showed that radiation defects are created at the Si-SiO\textsubscript{2} interface of the thicker magnetron-sputtered oxide (100 nm) during its deposition. The concentration of the radiation defects induced in MOS structures by MeV electrons depends also on the oxide thickness. The defects concentration at the Si-SiO\textsubscript{2} interface of these structures is higher than in the MOS structure with a thinner oxide (20 nm) film irradiated under the same conditions. A possible reason is the higher defects concentration generated in the thicker magnetron sputtered oxide during its deposition.

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