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# MeV electron irradiation of $O^+$ or $P^+$ implanted $Si-SiO_2$ structures♣

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$O^+$ or $P^+$ ion implanted $Si-SiO_2$ structures irradiated by high-energy electrons have been studied using Rutherford back-scattering spectroscopy in combination with a channelling technique (RBS/C). The samples were implanted by a dose of $10^{12}$ $cm^{-2}$ of $O^+$ or $P^+$ ions, and then irradiated by two doses of 20 MeV electrons – $2.5x10^{13}$ $el.cm^{-2}$ and $1x10^{15}$ $el.cm^{-2}$. The changes in the silicon and oxygen concentrations of the implanted samples were observed after electron irradiation. Such changes have been previously observed in $Si-SiO_2$ structures implanted by a higher dose ($10^{16}$ $cm^{-2}$) of $Si^+$ ions followed by MeV electron irradiation. The results showed that the type of implanted ion determines the concentration changes observed in the samples after high-energy electron irradiation. In the case reported here, the RBS/C spectra demonstrate that the 20-MeV electron irradiation increases the oxygen and silicon concentrations in $Si-SiO_2$ samples implanted by $O^+$ ions only, connected with the displacement of these atoms from their normal lattice sites.

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## 1. Introduction

Investigation of the secondary irradiation of pre-implanted $Si-SiO_2$ structures shows a variety of processes depending on the kind of post-irradiation, its energy and dose as well as on the ion implantation parameters. In the double treatment (implantation and high-energy electron irradiation) of $Si-SiO_2$ structures, the defect generation with high energy electron irradiation depends on the location of the preliminary implanted ions with respect to the $Si-SiO_2$ interface. When the implanted ions are located close to the n-type $Si-SiO_2$ interface, high-energy electron irradiation mainly creates defects associated with vacancy-oxygen (A-centre) and vacancy-phosphorus (E-centre) complexes [1].

The influence of high-energy electron irradiation on the implanted $Si-SiO_2$ structures with different doses of $Si^+$ ions has been investigated by Rutherford backscattering spectroscopy (RBS) [2]. Backscattering spectrometry has been used for the accurate determination of the elemental area density and impurity distribution in the thin films. Measurement of the number and energy distribution of ions backscattered from atoms in the near-surface region of the structures allows identification of the atomic masses and determination of the distribution of target elements as a function of depth below the surface [3-4]. In our earlier study, we showed that after electron irradiation, the redistribution of the oxygen and silicon atoms in the implanted $Si-SiO_2$ depends on the implantation dose. Oxygen and silicon atom redistribution in the samples implanted with $1x10^{12}$ $cm^{-2}$ $Si^+$ ions was negligible. A significant redistribution of these atoms was found only in $Si-SiO_2$ samples implanted with a higher dose of $10^{16}$ $cm^{-2}$ $Si^+$ ions. These results demonstrate that the structural changes at the silicon surface of implanted $Si-SiO_2$ samples, which take place after MeV electron irradiation, depend more strongly on the implantation dose than on the electron dose irradiation [2]. The aim of this work is to investigate the oxygen and silicon atom redistribution generated by MeV electron irradiation in $Si-SiO_2$ samples implanted by a low dose ($10^{12}$ $cm^{-2}$) of phosphorus or oxygen ions. Using Rutherford backscattering spectroscopy in combination with channeling, we found that MeV electron irradiation gives rise to oxygen and silicon atoms redistribution in the $O^+$ implanted samples only.

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## 2. Experimental details

The studies were performed with n-type <100> oriented silicon wafers with a resistivity of 4.7 Ω cm. The wafers were oxidized at 1050 °C in dry $O_2$ + 8 % HCl ambient up to 22 nm. The samples were then cooled in the same oxygen ambient at a rate of 1 C°/s. The oxide thickness was determined by ellipsometry. The Si-$SiO_2$ structures were implanted by $P^+$ or $O^+$ ions with an energy of 15 keV and a dose of $10^{12}$ $cm^{-2}$. The ion-beam energy of 15 keV was chosen so that the maximum number of the implanted ions would be deposited close to or at the Si-$SiO_2$ interface.

After implantation, both groups of implanted samples (with $P^+$ or $O^+$) were irradiated by different doses of 20 MeV electrons at a flux of about $10^{13}$ el/$cm^2$/s. Cooling was applied and room temperature was maintained during all irradiations of the samples. Three sets of samples were prepared from each of the two groups. The first set of Si-$SiO_2$ samples were implanted by $P^+$ or $O^+$ ions. The second set were implanted and then irradiated by 20 MeV electrons with a dose of $2.5x10^{13}$ el.$cm^{-2}$ and the third set was implanted and then electron irradiated with a dose of $1x10^{15}$ el.$cm^{-2}$. Each set of the group consisted of samples prepared under the same conditions so that any variation in samples within the set could be ruled out.

The electron irradiation was performed in vacuum ($10^{-3}$ atm) using Microtron MT-25 equipment at the Flerov Laboratory of Nuclear Reactions of the Joint Institute of Nuclear Research, Dubna, Russia, for different durations. No bias was applied to the MOS structures during the irradiation. The beam current was about $I_e$ = 9 μA. The distance between the Microtron window and the sample was 150 nm.

The Rutherford backscattering measurements were carried out at the National Institute of Advanced Industrial Science and Technology, Osaka, Japan. The RBS/C analysis was performed using a 1.8 MeV $He^+$ beam from a Van de Graaff accelerator in glancing angle geometry at 100°. The energy analysis of the backscattered ions was carried out by the detection system, yielding the backscattering spectrum displayed in the form of counts per channel vs. channel number. The RBS spectra obtained were processed and simulated by the RUMP computing code [5].

## 3. Results and discussion

It has already been shown that the density of defects introduced by high-energy electron irradiation in ion implanted Si-$SiO_2$ structures reaches a maximum when the damage maximum of the previously implanted ions is located close to the Si-$SiO_2$ interface [1]. In this study, we investigated such types of sample, namely, Si-$SiO_2$ samples with a thin (22 nm) oxide implanted by $P^+$ or $O^+$ ions. The distribution profiles of 15 keV implanted $P^+$ or $O^+$ ions in the structures at a dose of $10^{12}$ $cm^{-2}$ were calculated using the SRIM code [6]. The damage maximum of both types of implanted ion is located close to the Si-$SiO_2$ interface. The subsequent irradiation by 20-MeV electrons penetrates through the entire Si-$SiO_2$ structure and produces hard radiation defects (in both parts of the structure – the silicon dioxide and the silicon wafer, as well as at the Si-$SiO_2$ interface) which are not annealed at room temperature [7]. The high-energy electrons displace atoms from their normal sites in the semiconductor lattice of the silicon wafer, which results in the formation of vacancies and interstitial atoms. As a secondary effect, keV electrons are also generated by the 20-MeV electrons. We assumed that during electron irradiation, besides the implanted ions, oxygen and silicon atoms (displaced from their normal sites) are also able to migrate. That is why we studied the redistribution of the silicon and oxygen atoms in the Si-$SiO_2$ structures after high-energy electron irradiation. For this purpose, the silicon and oxygen concentrations were determined before and after each dose of high-energy electron irradiation, using the RBS/C spectra.

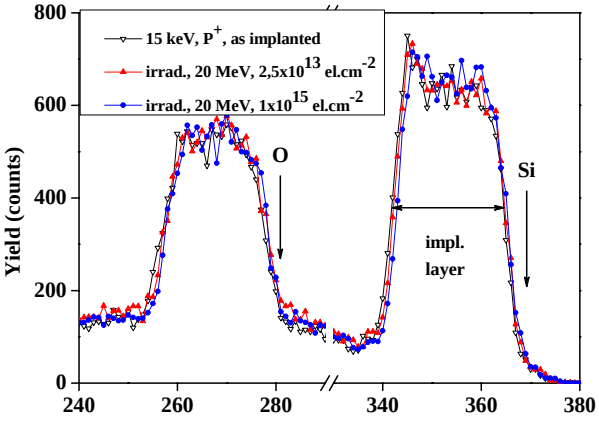


*Fig. 1. RBS spectra of n-Si-$SiO_2$ samples implanted by $P^+$ ions with a dose of $10^{12}$ $cm^{-2}$, and additionally electron irradiated with doses of $2.5x10^{13}$ el.$cm^{-2}$ and $1x10^{15}$ el.$cm^{-2}$.*

Fig. 1 shows RBS/C spectra of phosphorus-implanted Si-$SiO_2$ samples irradiated by 20 MeV electrons with doses of $2.5x10^{13}$ and $1x10^{15}$ el.$cm^{-2}$.

The measured thickness of the partially destroyed Si-$SiO_2$ structure after $P^+$ implantation is 54 nm, according to RUMP code [5]. It is in good agreement with the depth, theoretically calculated by SRIM, of formed implantation-formed amorphous layer, of 60 nm.

After both doses of electron irradiation, no significant changes in the RBS/C spectra of the samples were observed. Only a slight decrease (~2 nm) in the thickness of the created amorphous layer was observed after electron irradiation. The first peak of the RBS/C spectrum presents the oxygen concentration and the second one the silicon concentration in the amorphous layer on the surface of the sample. It is obvious that the two RBS/C spectra, measured after electron irradiation, almost repeat the

spectrum of the as-implanted sample. Obviously, the silicon and oxygen distribution at the Si-$SiO_2$ interface in phosphorus implanted Si-$SiO_2$ samples does not change after electron irradiation. We assume that the low dose ($10^{12}$ $cm^{-2}$) and the type of ion implantation (phosphorus) are the reasons for the negligible changes in the Si and O peak heights. This result is in a very good agreement with our previous results [2], where silicon redistribution in implanted Si-$SiO_2$ structures was observed only in the case in which $Si^+$ ion implantation was carried out with a higher ($10^{16}$ $cm^{-2}$) dose.

The RBS/C spectra of oxygen implanted and electron irradiated Si-$SiO_2$ samples are shown in Figure 2.

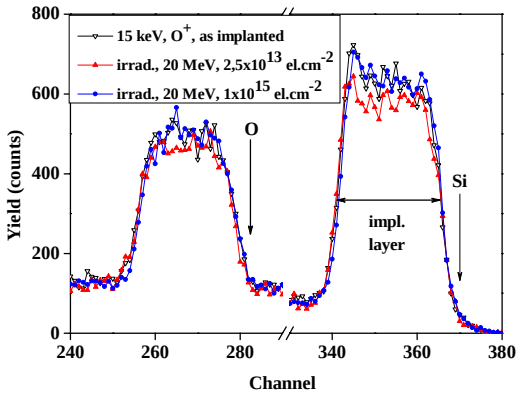


*Fig. 2. RBS spectra of n-Si-$SiO_2$ samples implanted by $O^+$ ions with a dose of $10^{12}$ $cm^{-2}$, additionally electron irradiated with doses of 2.5 x $10^{13}$ $el.cm^{-2}$ and 1 x $10^{15}$ $el.cm^{-2}$.*

The measured depth of the amorphous layer created by $O^+$ implantation was about 76 nm, according to RUMP code [5]; in good agreement with the calculated depth of 82 nm. The first dose of irradiation ($2.5x10^{13}$ $el.cm^{-2}$) resulted in a decrease of the height of the O and Si profiles, i.e. some of the O and Si atoms moved to lattice sites. Further irradiation with a dose of $1x10^{15}$ $el.cm^{-2}$ caused the formation of new vacancies and interstitial atoms. At the same time, a slight decrease in the thickness of the amorphous layer on the surface of the Si-$SiO_2$ sample was observed.

We noted earlier that high energy-electron irradiation leads only to an increase in the silicon concentration in silicon-implanted Si-$SiO_2$ structures [2]. The results in this work demonstrate that the same doses of electron irradiation result in a slight increase in both the oxygen and the silicon concentration at the Si-$SiO_2$ interface of oxygen implanted samples, i.e. an increased number of vacancies and interstitial atoms. Comparing the silicon profile increase with that of the oxygen profile in the RBS/C spectra, one can conclude that the amount of silicon accumulated is larger than that of oxygen. We assumed that, along with the generation of radiation defects during electron irradiation, oxygen radiation enhanced diffusion to the silicon substrate also takes place.

In [8], RBS has also been used to observe changes in the O/Si ratio.

## 4. Conclusions

It has been shown by RBS/C measurements that the silicon and oxygen concentrations of the implanted Si-$SiO_2$ samples (with $1x10^{12}$ $cm^{-2}$ $O^+$ ions) increase after high-energy electron irradiation. It is assumed that during electron irradiation, besides the implanted ions, the oxygen and silicon atoms (displaced from their normal sites) are also able to migrate to the Si-$SiO_2$ interface. The fact that a larger amount of silicon is accumulated at the Si-$SiO_2$ interface, compared to oxygen, is attributed to the generation of radiation defects during electron irradiation, and oxygen radiation enhanced diffusion to the silicon substrate takes place.

The results obtained are also interesting from a different point of view, as they demonstrate that implanting $P^+$ does not lead to changes in the oxygen and silicon re-distributions in Si-$SiO_2$ structures during high-energy electron irradiation.

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