Interface trap generation in MOS structures by high-energy electron irradiation

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Abstract. The changes of defect characteristics of MOS structures induced by irradiation with 23 MeV electrons are studied. The samples were irradiated for 30 or 120 s. The distributions of radiation induced interface traps, located at the Si/SiO₂ interface obtained from capacitance-voltage (C-V) characteristics and decomposition of multi-frequency conductance-voltage (G-V) characteristics, are dominated by distinct defects, with different localized energy levels in the Si bandgap. The interface traps are related with P⁰₁ and concentrations depending on irradiation time. The P⁰₁ concentration shows an order of magnitude increase as compared to the reference unirradiated sample, while P⁰₀ are found only after electron irradiation. The C-V characteristics indicate an increase of the positive oxide charge in SiO₂ due to generation of E’ defects. Defects in the Si bulk space charge region are also generated, which can be attributed to boron (V/B) and oxygen (V/O) vacancies complexes.

1. Introduction
In MOS devices the influence of ionising radiation on the electrical properties is of a special concern particularly with respect to reliability issues. In space or nuclear environment, the oxide layer of MOS structures may be subjected to high doses of ionising radiation, which is known to introduce traps in the oxide layers and at the interfaces. The generation of these traps subsequently may cause reliability problems and result in the degradation of the device electrical properties. The device parameters are affected by factors, such as type of ionizing radiation, time scale, dose, dose rate, device design, temperature etc. The electron beams in the present study have some special characteristics distinct from ions, neutrons and gamma irradiation.

The influence of radiation on the MOS structures has been extensively investigated through the years. Previous investigations on defect generation by irradiation with MeV electrons were concerned mostly to the low energy range [1, 2]. However, in order to achieve control over the radiation effects, it is important to gain detailed quantitative and qualitative information on the generated interface defect sites, when the MOS structures are exposed to high energy electron irradiation.

Our earlier experiments in the energy range of 11 to 23 MeV have shown creation of a spectrum of interface states in the silicon band gap. Some estimations of the energy depth in the Si band gap and capture cross section have been made [3] by means of TSC method. In the present contribution we describe the response of MOS structures to high-energy electron irradiation by assuming that it is the
result of three effects: (i) generation of interface traps, (ii) generation of oxide traps, and (iii) generation of bulk Si traps.

2. Experimental details

2.1 Sample preparation

The samples in this study were MOS capacitors prepared onto (100)p-type Si substrates with a resistivity of 44 Ohm.cm. Following standard RCA cleaning of silicon wafers, oxide layers with thickness of 50 nm, were grown at 1050 °C in dry oxygen ambient. After finishing the oxidation the Si/SiO$_2$ samples were cooled down in N$_2$ + O$_2$ ambient at a rate of 0.5 °C/s. MOS capacitors were formed by deposition of aluminium contacts with thickness 150 nm onto the oxide surface by thermal vacuum evaporation using a mechanical mask. To form an ohmic contact to the wafers, their back side was coated with a continuous thin Al layer.

The MOS structures were irradiated with 23 MeV electrons from the gate side parallel to the sample normal. The electron irradiation was carried out in vacuum at Microtron MT-25, in Flerov Laboratory of Nuclear Reactions of Joint Institute of Nuclear Research, (FLNR, JINR) Dubna, Russia. The distance between the Microtron window and the samples was 150 mm. The samples were bombarded with a flux of electrons, for different durations for 30 or 120 s, i.e. different irradiation doses. The average anode current of the electron beam at the samples was about 9 μA. At this energy, the electrons penetrate throughout the whole capacitor. No bias was applied to the devices during irradiation. Part of the MOS structures was left unirradiated to be used as reference samples for control measurements and comparative purposes.

2.2. Measurements

The electrical properties of the MOS samples were examined by means of capacitance–voltage (C/V) and conductance-voltage (G/V) measurements performed at different frequencies from 500 Hz to 300 kHz at the room temperature. The measurement unit was a Precision Component Analyzer (WAYNE KERR 6425). These characteristics were analyzed in order to determine the distributions of radiation induced interface traps, located at the Si/SiO$_2$ interface, and to evaluate induced oxide charge in SiO$_2$ layer and the bulk traps in the Si space charge region after the high energy electron irradiation. The densities of the interface traps $D_{it}$ were inferred from standard HF C-V analysis comparing the measured and the ideal curves. The bulk traps were approached from analysis of the G-V curves.

The thickness of the oxides was determined by ellipsometry method, using a high precision Rudolf Research ellipsometer in the wavelength range of 280-820 nm, at an incidence angle of 70º with an accuracy of ±0.2 nm.

3. Results and discussion

Radiation effects in MOS devices occur in the relatively thin noncrystalline dielectric films and at the dielectric film/silicon interfaces. Accumulation of charges can be traced by analyzing the behavior of the electrical characteristics of the MOS structures. In figure 1 (a) and (b) the high frequency C-V and G-V curves, measured at 300 kHz, are displayed for the two irradiation durations. The C-V curve for the reference unirradiated oxide is also presented. The shape of the C-V curves and comparison with the reference oxide in figure 1 (a) shows typical for increased density of interface traps. The 120 s electron irradiation results in two overlapping peaks in the G-V curves in figure 1 (b). For the 30 s this is not obvious and the multiple peaks are visible only after decomposition as shown below.

The shifts of the C-V curve for irradiated oxides to more negative voltages indicate higher density of oxide traps. The fixed charge in the oxide of MOS structure was evaluated from the flat-band shifts between the experimentally measured C-V curves and theoretically calculated ideal C-V curves for the case of oxide without any interface and oxide charges. The oxide defect densities are given in table 1. It can be seen that the after irradiation the oxide charge increases over the initial fixed charge in the oxide of the reference sample. The increased positive oxide charge is usually attributed to the E'
center, i.e. an oxygen-vacancy where each Si is back-bonded to three oxygen atoms. Note that the value for the smaller irradiation time is higher. However, this has to be attributed to the higher interface trap density in the lower part of the Si bandgap as will be seen below. The charge captured in these traps appears causes additional shift of the C-V curve, which results in higher density of the fixed oxide charge.

![Figure 1](image1)

**Figure 1.** C-V (a) and G-V (b) characteristics of 23 MeV electron irradiated MOS structures for 30 and 120 s. The flatband voltages are marked with arrows.

| MOS structures | \( Q_{fb} \) (cm\(^{-2}\)) | \( P_{b0} \) (eV\(^{-1}\)cm\(^{-2}\)) | \( P_{b1} \) (eV\(^{-1}\)cm\(^{-2}\)) |
|----------------|-------------------------------|-------------------------------|-------------------------------|
| Reference      | \( 1.5 \times 10^{11} \)     | -                            | \( 1.8 \times 10^{11} \)     |
| Irradiated 30 s| \( 9.0 \times 10^{11} \)     | \( 4.5 \times 10^{12} \)     | \( 1.8 \times 10^{12} \)     |
| Irradiated 120 s| \( 8.0 \times 10^{11} \)     | \( 6.8 \times 10^{12} \)     | \( 2.8 \times 10^{12} \)     |

**Table 1.** Fixed oxide charge \( Q_{fb} \) and concentrations of \( D_{it} \) at the \( P_b \) defect centers.

The interface traps density distributions \( D_{it} \) obtained from the 300 kHz C-V characteristics are shown in figure 2. Increase in interface defect concentrations with irradiation dose increasing is evident.

![Figure 2](image2)

**Figure 2.** Interface trap profiles in the Si bandgap of irradiated MOS structures for 30 and 120 s. The profile for the reference sample is also given.
The steep rise of interface trap concentration near valence band edge for 30 s irradiation is seen as a higher density of the positive oxide charge in Table 1. The interface trap distributions exhibit peaks in the lower part of the Si bandgap on side of the valence band. These peaks are attributed to that localized defect interface states. It can be seen that defects with close energy positions are observed for both irradiation times. This suggestion is confirmed by the analysis of the G-V characteristics. The shape of these curves in Figure 1 (b) indicates the presence of localized states. This is especially evident for the MOS capacitor irradiated for 120 s. The localized states can be better seen after decomposition of the G-V curves as given in Figure 3 (a) and (b).

Figure 3. Decomposition of the G-V characteristics of irradiated by 23 MeV electron irradiation for 300 kHz for 30 s (a) and for 120 s (b) p-type MOS structures.

Usually radiation-induced interface states in oxides grown on silicon (defined as electronic levels located spatially at the oxide/Si interface and energetically within the band gap of the Si) are correlated with ESR active defects referred to as P\textsubscript{b} centers [4-6]. Their concentrations are given in Table 1. It is well established that on (100)Si, a twofold P\textsubscript{b} centre, i.e. P\textsubscript{b0} and P\textsubscript{b1}, are present [4]. Energetically they appear at the positions shown in Figure 2, and are most probably donor type as discussed in ref. [7]. The P\textsubscript{b0} is a dangling Si bond with three Si back bonds (• Si ≡ Si\textsubscript{3}), while the structure of the P\textsubscript{b1} center has remained controversial for a long time, and was first ascribed to dangling Si bonds with two Si and one O back bonds [4]. Recent studies [8] have confirmed the suggestion for the P\textsubscript{b1} to be a Si dangling bond in a strained Si-Si dimer configuration [9]. Irradiation is known to cause greater increases in the P\textsubscript{b0} than the P\textsubscript{b1} [10]. In our case the P\textsubscript{b1} center is better seen only after the irradiation for both durations, but is more pronounced at 120 s. The P\textsubscript{b1} concentration is about an order of magnitude greater as compared to the reference unirradiated sample, while P\textsubscript{b0} are found only after electron irradiation. The concentrations of both P\textsubscript{b0} than the P\textsubscript{b1} show 1.5-fold increase for 120 s as compared to 30 s irradiation.

Contribution of bulk traps [11], i.e. traps that reside in the space charge region in the Si substrate is detectable only by the G-V technique. The bulk traps manifest their presence as peaks in G/ω versus ω curves, with positions independent of the gate voltage, as shown in Figure 4 (a) and (b). The capture cross section for 30 s irradiation is 1.2x10\textsuperscript{-14} cm\textsuperscript{2}. Defects in Si substrate with similar parameters have been found in earlier TSC and DLTS experiments and attributed to di-vacancies and Si atoms recoiled from the Si/SiO\textsubscript{2} interfaces that migrated into the Si lattice [12, 13]. As it has been already shown the main defects created by high-energy electron irradiation in MOS structures are related to the main impurities in the Si substrates [12]. In our case (p-Si), boron is the main impurity of the Si substrates, and consequently, the defects are related to boron-vacancy and oxygen-vacancy defect complexes.
4. Conclusions

Generation of three different types of defects was observed in MOS structures subjected to high energy electron irradiation of 23 MeV as revealed by the analysis of the C-V and G-V characteristics. The interface traps that are located at the interface exhibit distinct energetic levels in Si bandgap. The defects were identified as donor type \(P_{b0}\) and \(P_{b1}\) centers, with concentrations depending on irradiation dose. The \(P_{b0}\) center was found only in irradiated samples. Positive oxide charge build-up was established upon irradiation due generation of \(E'\) centers. The higher density of this charge for the lower dose is attributed to the higher interface density near the valence band edge seen in the interface trap distribution. Bulk defect are also generated in the Si substrate which are ascribed to boron-vacancy and oxygen-vacancy defect complexes.

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