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Dose responses of the SiO_2 used in radiation sensors in field effect transistor form

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ABSTRACT

Aim: To investigate the structural changes in the SiO_2 (silicon dioxide) layer, which is the sensitive region of the RadFET radiation sensors used in the medical field, and to elaborate the impacts of these modifications on electrical characteristics.

Methods: Dry oxidation method was used to grow the SiO_2 film on n-type Si (100) and SiO_2 MOS capacitors were produced by using DC magnetron sputtering. Irradiation was carried out using a ^{60}Co radioactive source at a dose range of 1 kGy-50 kGy. XRD (X-ray diffraction) results showed that no crystalline structure was formed in the studied dose range.

Results: The results obtained from XPS (X-ray photoelectron spectroscopy) showed that Si-Si oxygen deficient bonds were formed in the post-production structure, resulting in the observation of flat band voltage (V_{fb}) at negative values.

Conclusions: In general, the Si-Si oxygen deficient bond content increased with increasing radiation dose, causing the C-V curve to shift towards larger negative voltage values as desired. The device sensitivity was almost constant after 25 kGy.

Key words: RadFET, NürFET, MOS, structural modifications, radiation dose.

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Introduction

The usability of Metal-Oxide-Semiconductor-Field Effect Transistors (MOSFETs) as radiation sensors was first demonstrated by Holmes-Siedle [1], followed by intense research into the use of these dosimeters in different fields. Optimized for the purpose of improving radiation sensitivity, p-channel MOSFETs (also known as RadFETs) are used to obtain information about space-radiation in spacecraft [2], to determine the radiation damage that may occur in electronic components in centers such as CERN where the experiments with high radiation field are conducted [3], and to detect the possible radioactive leakage in nuclear power plants. The forms of these chips placed in the wristwatch are attached to military personnel and serve as a warning system in case of possible radioactive danger [4]. RadFETs are used in skin dose measurements in radiation chest treatment, treatment planning verification (for photon and electron) in IMRT, in measurements of input-output doses, skin dose, peripheral dose and tumor dose, in IGRT (Image Controlled Radiotherapy), TBI (All or Half body irradiation), Brachytherapy, Stereotactic radiosurgery/stereotactic radiotherapy (SRC/SRT) [5].

The first domestic production of RadFETs was made at Bolu Abant Izzet Baysal University Nuclear Radiation Detectors Application and Research Center (NRDC), and these dosimeters, in which two sensors were placed in a single chip, were named NürFET. The sensitive region of the commercial RadFETs/NürFETs consists of silicon dioxide (SiO_2). The most important reason of this choice is that SiO_2 has high thermodynamic stability with Si and creates excellent interface quality. On the other hand, studies are being carried out on alternative high-k dielectrics to SiO_2 in order to obtain thinner and more sensitive sensors [6].

The calibration of a NürFET radiation sensor is based on the shift in threshold voltage depending on the applied dose. The initial threshold voltages of p-channel NürFETs are observed at negative voltage values, and with the applied dose, the threshold voltage shifts towards larger negative voltage values since the holes are more trapped in the structure than electrons. The most serious problem with high-k/MOS structures is the poor interface quality, and the +3 oxidation level acting as an electron trap center [7]. In some cases, electrons are trapped more in the oxide layer and/or at the interface than in the holes, resulting in electrical characteristics not shifting in the desired direction [8].

Thermal annealing is a common method applied to the structure to remove some defects in the thin film. However, this causes some defects in the structure to not be permanently repaired, resulting in the formation of neutral electron trap centers [9–11]. In addition, since radiation causes local heating in the structure, it creates structural changes [12]. For these reasons, it is extremely important to determine what kind of changes the radiation dose causes in the structure and to define their effects on electrical characteristics. The aim of this study is to describe the structural changes caused by gamma radiation in the SiO_2/Si structure annealed at room temperature (RT) and to detail the effects on the radiation response of a SiO_2-MOS capacitor.

Materials and methods

The possible contamination on 6 inch-n type Si (100) wafer was removed by following the RCA procedure. Dry oxidation method was used to deposit the SiO_2 layer. After the Si wafers were placed in the diffusion furnace, oxygen gas with 3 slm flow rate was sent into the system. Film deposition was made for 2 hours 53 minutes at 1000 ^oC and then the samples were placed in a nitrogen cabinet at room temperature. The thickness of the film was measured at 100 nm with Spectroscopic Reflectometer. A part of the 6-inch wafer is reserved for structural analyses, XRD and XPS. The remainder was used for the production of MOS capacitor.

Metal electrodes of SiO_2-MOS capacitors were created with a DC magnetron sputtering system using a 99.9% purity 4-inch Al target. After the pressure of the vacuum chamber of the sputtering system was reduced to $6.0x10^{-4}$ Pa, argon gas with the flow rate of 16 sccm and the pressure of 1.0 Pa was sent into the system to form plasma. While the front contacts were formed, a 1.5 mm diameter mask was placed on the upper side of the film-covered surface of the structure and Al deposition was performed for 55 minutes at 150 W. For the back contact, the entire matte part of the wafer is covered with Al under the same conditions for 25 min. Production stages were carried out in 10, 100, 1000 clean room laboratories in NRDC.

The SiO_2/Si structures and SiO_2-MOS capacitors were irradiated with ^{60}Co gamma radioactive source (1.3 kGy/h) at 1 kGy, 25 kGy, 50 kGy at the Turkish Atomic Energy Authority.

The crystal properties of the film were evaluated with XRD analyses and the spectra were taken for the diffraction angle range of 10°-80°. XPS measurements of the SiO_2/Si were conducted by using Physical Electronics PHI 5000 VersaProbe (Monochromatic Al Kα X-ray source-1486.6 eV). Depth profiles for the surface, mid of the film and oxide/interface were measured with Ar sputtering (1 keV) to determine the atomic concentrations and bonds. The Si 2p and O 1s XPS spectra were corrected with reference to the C 1s peak of 284.8 eV. De-convolution of the spectra was performed with XPSPEAK 4.1 software.

The electrical characteristics of SiO_2 MOS capacitors were measured by HIOKI-LCR meter at two different frequencies (100 kHz and 1 MHz).

Results and Discussion

The XRD spectra of the SiO_2/Si structures irradiated at three different doses are presented in Figure 1. No peaks were observed indicating crystallization before and after irradiation, indicating that the structure is amorphous. It is important that the structure maintains its amorphous property in the studied dose range in terms of exhibiting a stable behavior.

Figure 2 shows typical Si 2p and O 1s XPS spectra obtained from SiO_2/Si structure. No carbon content was found in layers other than the surface. The peak centered at ~98.6 eV in the Si 2p spectrum represents Si-Si bond, while the peak located at ~103.3 eV shows Si-O-Si bond. In the O 1s spectrum, the peak centered at ~532.2 eV is associated with the Si-O-Si bond. Since hydroxyl species adversely affect the electrical characteristics of the sensor, it is desirable that it is not in the structure or observed at a minimum level. No peaks were observed indicating the presence of hydroxyl species in the film.

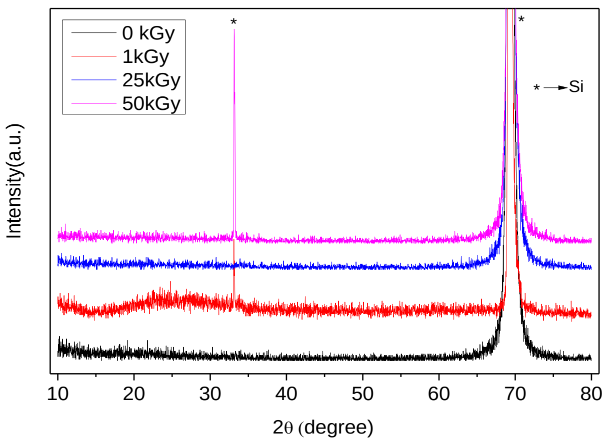

Figure 1. XRD spectra of the SiO_2/Si structures irradiated in the dose range of 0-50 kGy.

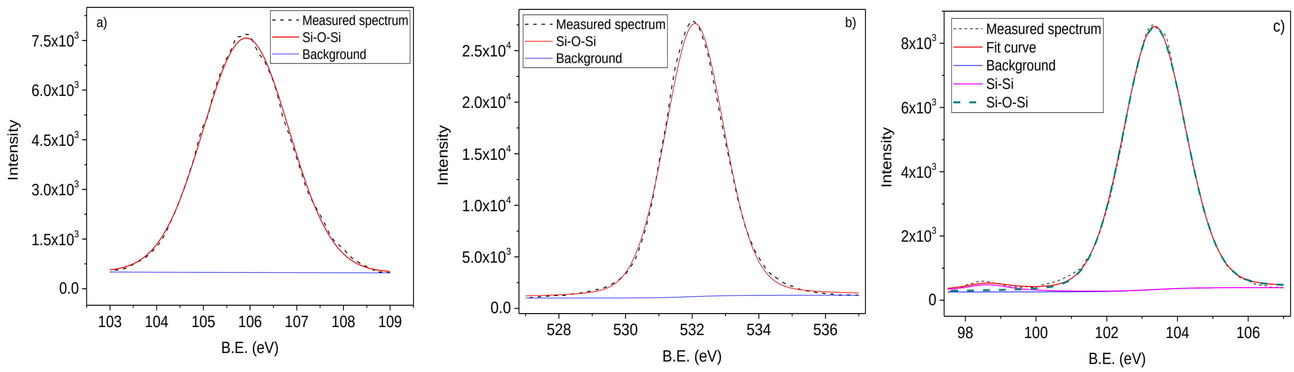

Figure 2. SiO_2/Si XPS spectra: a) Si 2p for film, b) O 1s for film, c) Si 2p for interface.

Depth-dependent variations of atomic concentration (A.C.) values of Si and O in non-irradiated and irradiated SiO_2/Si structures are given in Figure 3.

indicating Si-Si bonds in XPS spectra was found only at interfaces. It has been reported that the Si-Si oxygen deficient bonds act as hole trap centers [13]. For this reason, positive

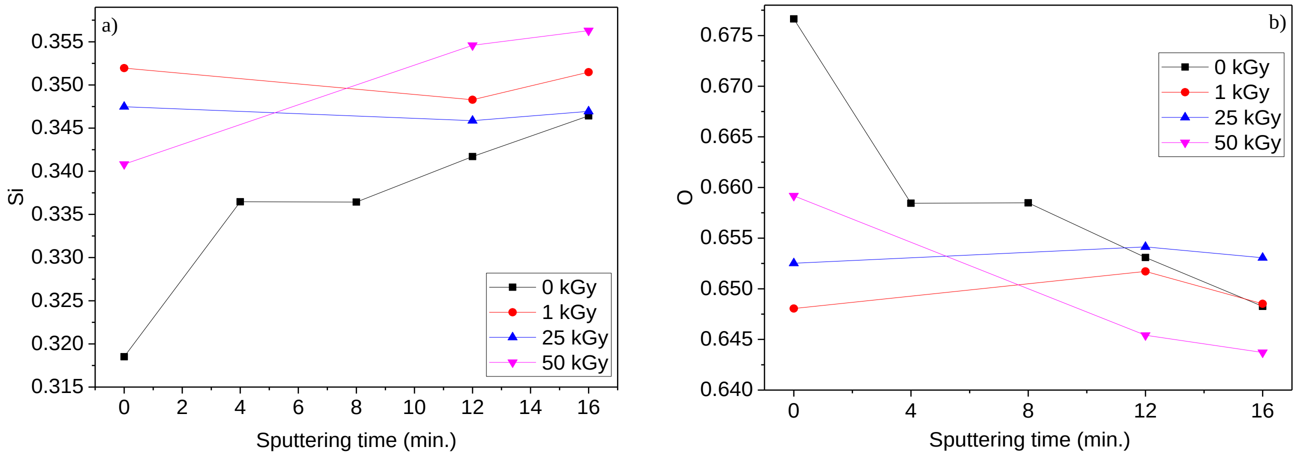

Fig. 3. Depth-dependent Si and O atomic concentrations: a) Si, b) O.

It is theoretically expected that there will be 33.3% Si and 66.7% O in the structure. The results in Figure 3 show that the production meets the theoretical expectation to a great extent. Figure 4 shows the variation of the signal intensity of the Si-O-Si peaks in the O 1s spectra depending on depth of the film.

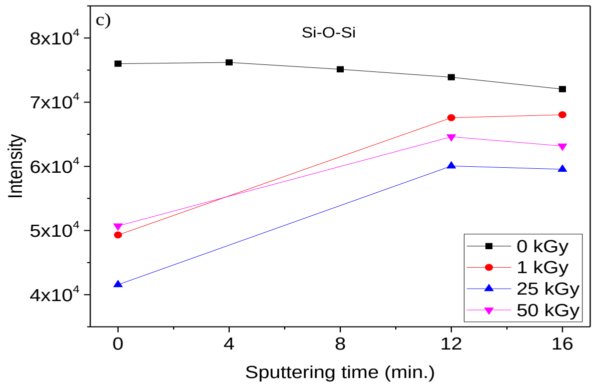

Figure. 4. Intensities of the Si-O-Si peaks in the O 1s spectra.

Post-production Si concentration was generally above 33.3% at all depths as can be seen from Fig. 3. This indicates oxygen deficient Si-Si bonds in the structure that do not participate in bonding with oxygen. However, since the signal intensity is weak, a second peak

charges are expected to be more dominant than negatives in the post-production structure. Si concentration increased with the irradiation of 1 kGy in the film and oxygen content decreased. Although the Si concentration is high at 1 kGy compared to 0 kGy, the oxygen concentration is similar to the values obtained from the non-irradiated sample. On the other hand, the Si-O signal intensity is also lower than the values obtained from the non-irradiated sample. These results indicate an increased concentration of defects acting as positive charge trap centers both in the oxide layer and at the interface. Therefore, the C-V curve is expected to shift to the left with 1 kGy irradiation, compared to the pre-irradiation electrical characteristic. The Si concentration in the film and at the interface is generally high at 25 kGy compared to the values obtained from the non-irradiated structure, and lower than the values obtained at 1 kGy. The oxygen concentration at 25 kGy tends to be higher than values obtained from irradiated at 1 kGy and non-irradiated structures. When the irradiated structure at 25 kGy is compared with the non-irradiated structure, it is seen that although the Si concentration at the interface is at a similar level, the oxygen concentration is higher at 25 kGy, resulting in a less positive charge defect center content at the interface at 25 kGy. On the other hand, the difference between Si concentrations in the film is higher than the difference between oxygen concentrations. This means that the positive charge trap center concentration in the film at 25 kGy is higher than in the non-irradiated structure. Therefore, the electrical characteristics are expected to be more left compared to those obtained from the non-irradiated structure after 25 kGy irradiation. When the results of 25 kGy and 1 kGy are compared in terms of atomic concentrations, it is expected that the positive charge trap center content in the structure at 25 kGy is less. However, as can be seen from Figure 4, Si-O content is lower at 25 kGy. The absence of oxygen in the Si-O-Si bond may have caused an increase in the Si-Si content in the structure. Therefore, it can be said that positive charge traps are higher at 25 kGy compared to 1 kGy. The Si concentration was found to be the highest and the oxygen concentration the lowest at all depths except the surface at 50 kGy. Although Si-O-Si ratio is higher compared to 25 kGy, differences in atomic concentration may have caused an increase in positive charge traps at 50 kGy.

The series resistance is very effective on the electrical characteristics of the MOS capacitor. Therefore, the series resistance correction, which is explained in detail in the Ref. [14], is applied to the data. The corrected C-V characteristics for 100 kHz and 1 MHz of the SiO_2 MOS capacitor taken between -25 V – 15 V before and after irradiation were given in Figure 5.

The dielectric constant of the non-irradiated SiO_2 was calculated as 4.70 using the well-known formula, $C = \varepsilon\varepsilon_o A/d$. The dielectric constant of SiO_2 is 3.9. The reason of the higher value found in this study is that interface trap charges contribute to the measured capacitance [15]. Interface trap charge density (N_{it}) was calculated using Eq. 1 [16]:

$$N_{it} = \frac{2}{qA}\frac{G_{max}/\omega}{\left(\frac{G_{max}}{\omega C_{ox}}\right)^2 + \left(1 - \frac{C_m}{C_{ox}}\right)^2} \qquad (1)$$

where G_{max} is the maximum conductance, ω is the angular frequency, C_{ox} is the oxide capacitance, C_m is the capacitance related to maximum conductance, q is the electrical charge and A is the capacitance area. Post-production N_{it} value was obtained as $5.3x10^{10}$ $eV^{-1}cm^{-2}$. The change in oxide trap charge density (ΔN_{ox}) occurred with the irradiation was calculated in the following expression [17]:

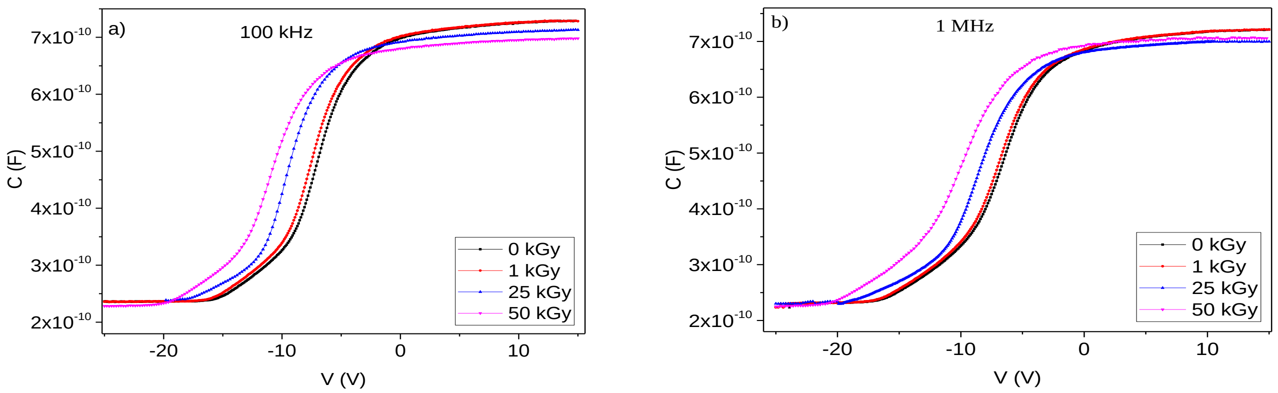

Fig. 5. C-V curves of SiO_2 MOS capacitor before and after irradiation:a) 100 kHz, b) 1 MHz.

$$\Delta N_{ox} = -\frac{C_{ox}\Delta V_{mg}}{qA} \qquad (2)$$

where ΔV_{mg} is the change in mid-gap voltage. The ΔN_{it} (change in the interface trap charge density with dose) and ΔN_{ox} values depending on the dose are given in Figure 6a. No major change in the ΔN_{it} values was observed in both frequencies with increasing dose, indicating that the device performance is not adversely affected in the dose range studied. ΔN_{ox} values increased with increasing dose as expected. Device sensitivity was calculated by dividing V_{fb} by dose and the values are given in Figure 6b. The sensitivity of 25 kGy and beyond is almost similar, indicating that the device has reached saturation.

were investigated by XRD and XPS techniques. In addition, a connection was established between the electrical characteristics and structural analysis of SiO_2 MOS capacitors. SiO_2 film preserved its amorphous character up to 50 kGy. XPS results showed that mainly oxygen deficient Si-Si bonds were formed in the structure with production and irradiation. Si-Si defect content tends to increase with increasing radiation dose. An increase in oxygen concentration does not always indicate less oxygen deficient bond. In addition to the oxygen concentration, the formation of Si-O-Si bond is also effective on electrical characteristics. There is no important change in the N_{it} with the increasing radiation dose, indicating that the performance of the device does not deteriorate up to dose of 50 kGy. The

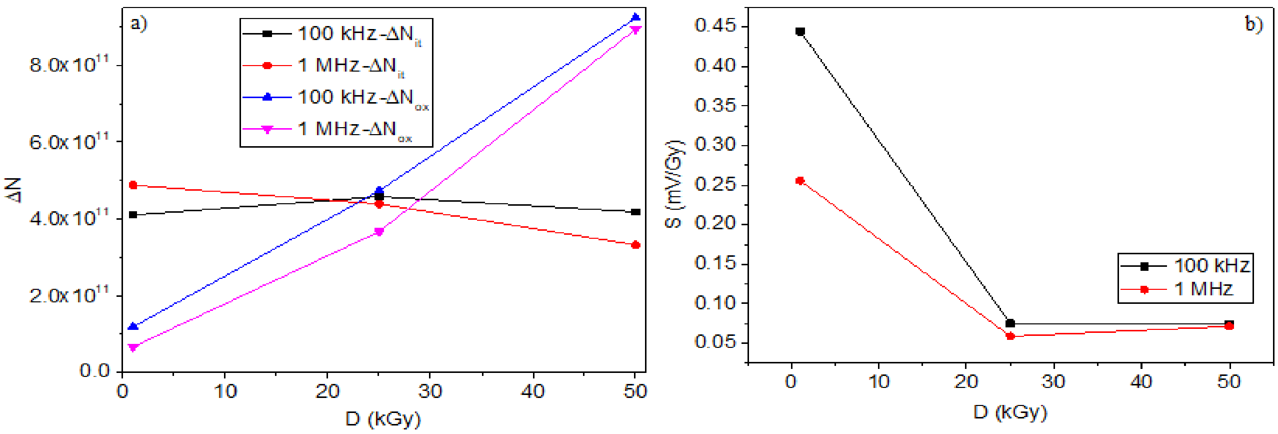

Fig. 6. a) Sensitivity, b) Dose-dependent $\Delta \boldsymbol{N}_{ox}$ and $\Delta \boldsymbol{N}_{it}$ values of the SiO_2 MOS capacitor.

The radiation response of the MOS capacitor with a 240 nm thick SiO_2 layer for 64 Gy is reported as 4.03 mV/Gy [18]. An increase in the thickness of the sensitive region can improve the sensitivity of the sensor. On the other hand, it is known that the dose response deviates from linearity as higher doses are reached [19,20].

Conclusion

Structural modifications in SiO_2/Si structure that occur after production and with irradiation

ΔN_{ox} values increased with increasing radiation dose as expected. Since the device was saturated at 25 kGy and beyond, there was no significant change in its sensitivity after this dose. The focus of future studies should be determining the types of traps in devices produced with different dielectrics and improving the sensitivity of the sensor.

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Conflict of Interest: *The authors declare that they have no conflict of interest.*

Open Access Statement

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