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A systematic study on MOS type radiation sensors

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Abstract

Radiation sensors based on metal oxide semiconductor (MOS) structure are useful because of their superior sensitivity as well as excellent compatibility with the existing microelectronic technology. In this paper, a systematic study of MOS capacitors built on p- and n-type Si substrates with different SiO_2 thicknesses (10 nm, 50 nm, 100 nm and 240 nm) is presented. MOS device response to gamma radiation up to 256 Gray have been studied from the sensor application point of view. Variation of the radiation induced device response with oxide thickness, substrate type, applied bias and post annealing have been measured and discussed. Radiation induced charge in MOS devices is shown to be a strong function of the oxide thickness as expected. Application of a positive bias to the gate is found to enhance the device sensitivity for both n- and p-type devices. This is explained in terms of the involvement of the interface states in the sensing process. Devices have also been studied after repeated cycles of irradiation and annealing treatment under hydrogen atmosphere. Each cycle consists of gamma irradiation with 60 Gray dose and an anneal at 200 °C for 30 min. The charging–discharging mechanism during these cycles is discussed.

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1. Introduction

The study of the radiation effects on MOS based devices, including MOS capacitors, has been an active research area over the past decades. The primary motivation behind these studies is to provide useful and systematic information regarding the behavior of MOS devices and their usage in nuclear radiation dosimetry.

Radiation sensors require high sensitivity and linear performance over the intended energy range, real-time response, low noise and acceptable reliability [1]. Different materials, geometric arrangements and physical detection techniques have been used to meet these requirements. Among these, MOS based radiation sensors have attracted special attention because of their superior sensitivity as well as the excellent compatibility with microelectronics technology. Numerous efforts have been devoted to investigate the influence of radiation on the MOS structure and to understand its response to ionizing radiation [2,3]. The influence of radiation on MOS characteristics depends on both the dose and the parameters of the device structure including the oxide thickness [4].

The effect of radiation on *C–V* characteristics is seen as a flat band voltage shift towards negative gate voltages when exposed to gamma rays or to other ionizing radiation. This is due to the formation of positively-charged trap centers in the oxide and/or the SiO_2/Si interface on exposure to radiation. The effect of process and device parameters on the device performance has been the subject of many investigations [5–7]. Some groups examined the radiation response of MOS capacitors after ac and dc bias using *C–V* analysis and report no significant frequency dependence for either

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total trapped positive charge density or negative trapped charge density during ac bias exposure [8]. The suitability and usability of MOS devices as a radiation sensor depends on the device sensitivity which is directly related to the gate oxide thickness. It has been shown that thicker gate oxides exhibit a greater voltage shift for a given dose. However, for a heavy radiation dose, a device with a thin oxide is preferred to limit the radiation induced damage. The type of the trap states responsible for the voltage shift has been addressed in several studies in which it was shown that the voltage shift is mostly due to trapped oxide charges rather than interface states [9–11]. However, in our previous work we showed that dynamic interface states located at, or in the vicinity of, the interface play also a significant role in the observed voltage shift [12]. The effect of bias has also been studied to some extent, and it was shown that doses as low as 50 mRad can be easily measured when a 40 V bias is applied to a device [13,14]. Jaksic et al. [15] investigated the effect of bias on the sensitivity of RadFETs and showed that positive bias enhances the formation of oxide-trapped charge and interface traps.

In our previous work we studied the recovery of device performance by a post-usage annealing process, and thus its reusability in practical applications [12]. Most of the radiation induced positive charges can be annealed out at temperatures as low as 150 °C [12]. Other groups have demonstrated experimentally that thermal treatment of MOS structures at 400 °C for 30 min anneals the irradiation induced defects [16–19].

Even though these and other reports [20–22] have provided some insight, the radiation hardness and dependence of device performance on process and device parameters have not been fully reported. The dependence of device operation on substrate orientation type, which might be important in the creation and annealing of the trap charges, has not been studied. A simultaneous study of the effect of bias and orientation type may be useful in understanding charge movement during ionization/annealing processes. It is also of interest to understand how exactly the radiation response varies in terms of the charge created in the oxide layer.

In this paper, we present a complete evaluation of radiation sensors based on a MOS structure. The dependence of device operation on the oxide thickness, the effect of post annealing, effect of applied bias and substrate orientation have all been studied in a systematic way. An evaluation of the device performance of the MOS based radiation sensors during their successive usage/recovery cycle as a result of irradiation/annealing processes is also given.

2. Experimental details

The MOS devices studied were capacitors fabricated on n- and p-type silicon (100) substrate with a nominal resistivity 10 Ω cm. Following a standard RCA cleaning process, oxide layers with a thickness of 10 nm, 50 nm, 100 nm, 240 nm were grown by dry oxidation in a clean room environment. The oxide thicknesses were determined by ellipsometry after oxidation. The ohmic contact to the devices was fabricated by evaporating Al and Au–Sb on the back side for p-type and n-type wafers respectively. The contacts were annealed at about 450 °C to complete the ohmic contact formation. Front electrodes of the MOS devices were made of circular dots formed by evaporating Al through a shadow mask.

In order to study the response of MOS capacitors to gamma irradiation over a wide range of doses, samples were irradiated using a Co-60 gamma source from 8 to 256 Gray at a dose rate of 0.018 Gy/s. *C–V* measurements were recorded before and after irradiation. The bias dependence was studied by application of positive or negative bias during irradiation. Shifts in the flat band voltage of the *C–V* curves were carefully determined. The measurements were repeated with many different samples to study the effects of oxide thickness, bias and orientation dependence on the response of MOS capacitors. The annealing/irradiation cycle was repeated for the sample with a 680 nm thick oxide irradiated to 60 Gray and annealed at 200 °C for 30 min in a hydrogen ambient.

3. Results and discussions

3.1. Dependence on oxide thickness

Radiation induced charges cause a shift in the position of the flat band voltage of a *C–V* curve along the voltage axis. Fig. 1(a) shows the measured shift in V_B upon exposure to gamma irradiation as a function of oxide thickness. ΔV_B was determined by the standard method [18]. This shift, always seen in the negative direction, is generally attributed to trapping of holes generated by radiation. It is believed that the electrons generated during ionization disappear into the metal contact or substrate leaving behind a hole in the oxide. The generated holes are trapped at oxide and/or interface defects which have not yet been identified. Fig. 1(b) shows the corresponding radiation induced charges as calculated from the equation

$$Q = \varepsilon(A/d)\Delta V, \tag{1}$$

where $\varepsilon = 3.9\varepsilon_0$ for SiO_2, A is gate area, d is oxide thickness. The number of radiation induced charges increases with the oxide thickness. This is consistent with what has been reported previously in similar studies. The behavior of ΔV as a function of oxide thickness can be explained by a quadratic function $\sim d^2$, where d is the oxide thickness. As also discussed in [7], holes trapped either at the Si/SiO_2 interface or with a fixed distribution through the oxide thickness are expected to produce a threshold or flat band voltage shift linearly proportional to oxide thickness, resulting in a radiation induced shift which is proportional to the square of the oxide thickness. On the other hand, the induced charge varies linearly with oxide thickness for thicker oxides in Fig. 1(b). This can be understood by considering the absorption of a gamma ray in the oxide. The

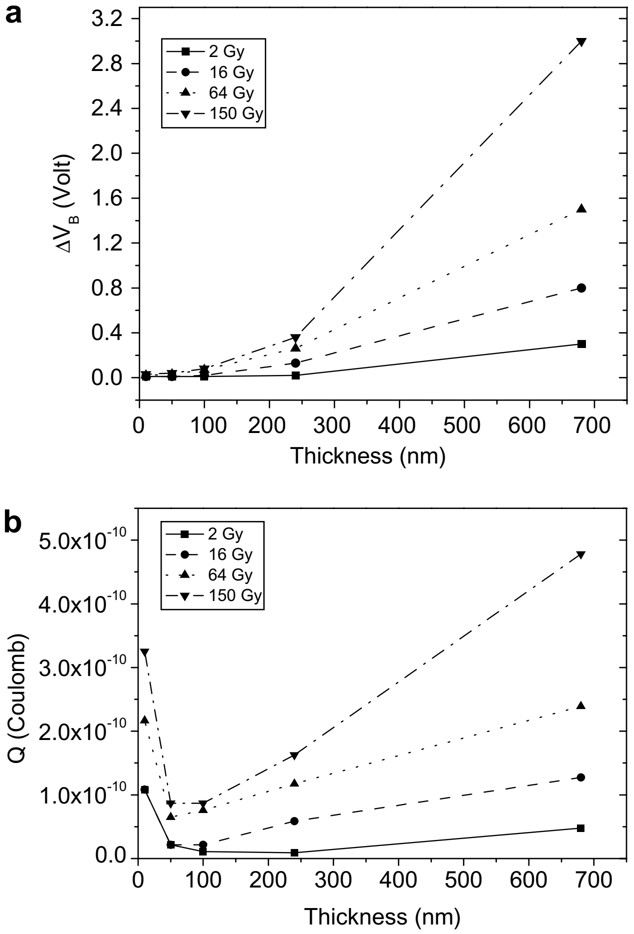

Fig. 1. (a) Flat band voltage shifts in p-type MOS capacitors with 10, 50, 100, 240 nm thicknesses. (b) Corresponding radiation induced charge as calculated from Eq. (1).

photon absorption through a solid film is described by an exponential relation $I = I_0e^{-\alpha x}$, where α is the absorption coefficient, x is the distance from the surface and I_0 is the incident photon intensity at the surface. If the layer thickness is small with respect to the absorption efficiency, the number of absorbed photons is linearly proportional to the thickness of the layer, i.e. $(I - I_0) \sim d$. Assuming that every single gamma ray generates same amount of positive charge in the oxide, the flat band voltage shift is found to be proportional to $\sim d^2$ from Eq. (1).

The reverse relation seen for thin oxides is likely to be related to the total reduction in the resistance of the film with radiation. We observed that the current transport through the SiO_2 film was enhanced, probably due to the easy conduction path formed as a result of radiation induced damage in the oxide. This enhancement in conduction leads to decreasing recombination with more positive trap charges in the film. However, the film quality degrades significantly in this regime because of the increased leakage current through the oxide.

The number of radiation induced charges per gamma ray was calculated from the flat band voltage shifts and total radiation calculated from the source and absorption. The flux of the gamma source in Eq. (2) below was assumed to be uniform through a spherical area, such that the total flux at a distance r from the source is given by the simple equation

$$\Phi = S/4\pi r^2, \tag{2}$$

where S is source strength (Curie or Becquerel) and $4\pi r^2$ is solid angle. The source strength was 73.398 Curie during the exposure. The photon flux hitting gate area was about 33,660 gamma rays per second per unit of area. This calculation is shown in Fig. 2, with each gamma ray generating much charge during its passage through the oxide. The radiation induced charge per incident photon seems to saturate at a constant value at high doses. At high doses the damage population becomes so high at the start of irradiation that each subsequent gamma ray interacts with already-damaged regions. A dynamic Monte-Carlo type calculation taking into account multiple interaction of the matrix with incoming photons would be useful to understand this process.

The oxide charge value extracted from the flat band voltage shift represents the total charge located inside the oxide and at the interface. In a previous publication [12], we reported on the amount of interface charge using conductance technique where the density of interface states exceeded $1 \times 10^{13}\ \mathrm{cm}^{-2}\,\mathrm{eV}^{-1}$ in irradiated samples. To compare the total oxide charge found from the flat band voltage shift and the interface state density one needs to find the total interface density across the bandgap. Also one needs to know whether these states are normally charged or uncharged with respect to the Fermi level. This is not possible with a single conductance measurement. A more rigorous analysis should be based on use of two different device type as described in [9].

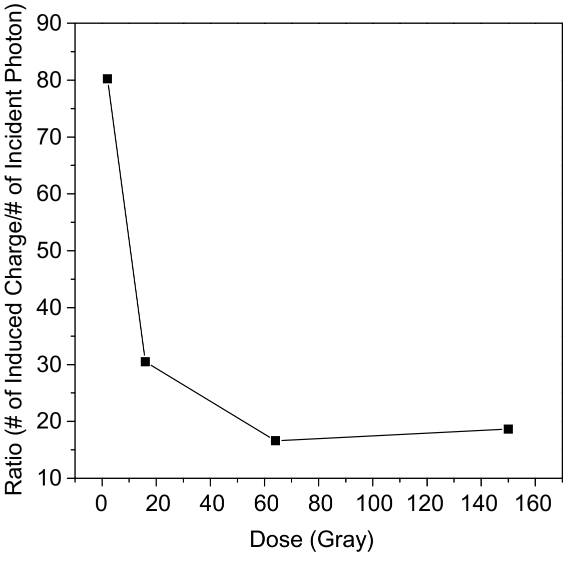

Fig. 2. Number of radiation induced charge per incident photon as a function of the dose.

3.2. Dependence on substrate type

The irradiation dependence of device response on the substrate type was studied experimentally, which is important both from technological and scientific points of view. *C–V* curves as a function irradiation for a p- and n-type substrate with 240 nm oxides are given in Fig. 3. The irradiation induced shift is in the negative direction for both substrate types, which shows that type of the induced charge is positive for both. This is consistent with what has been reported previously.

The radiation induced charge was calculated using Eq. (1) and shown in Fig. 4. The radiation induced charges increases with dose for both type MOS capacitors, but the rate of increase is less at high doses. From Fig. 4, based on the shift of the flat band voltage (which is close to the accumulation side of the *C–V* curves), p-type MOS capacitors are found to be more sensitive than n-type MOS capacitors. However, we note that the relative sensitivity depends on where the voltage shift is taken. It seems from Fig. 4 that n-type samples would have better sensitivity if the voltage shift was taken from region close to the inversion side of the curve. This is understandable because the voltage shift in the depletion region is a function of charge state of the interface states, which is a strong position of the Fermi level at the interface. It is well known that the Fermi level sweeps the interface with the applied bias and alters the charging states of the trap states. This is probably the case for the n-type samples.

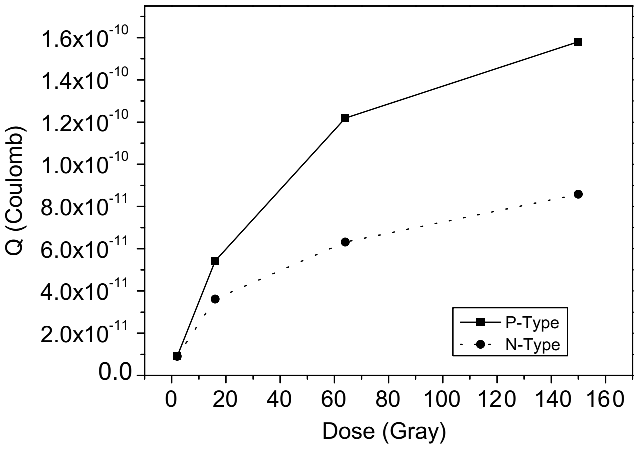

Fig. 4. Radiation induced charge versus dose for p- and n-type MOS.

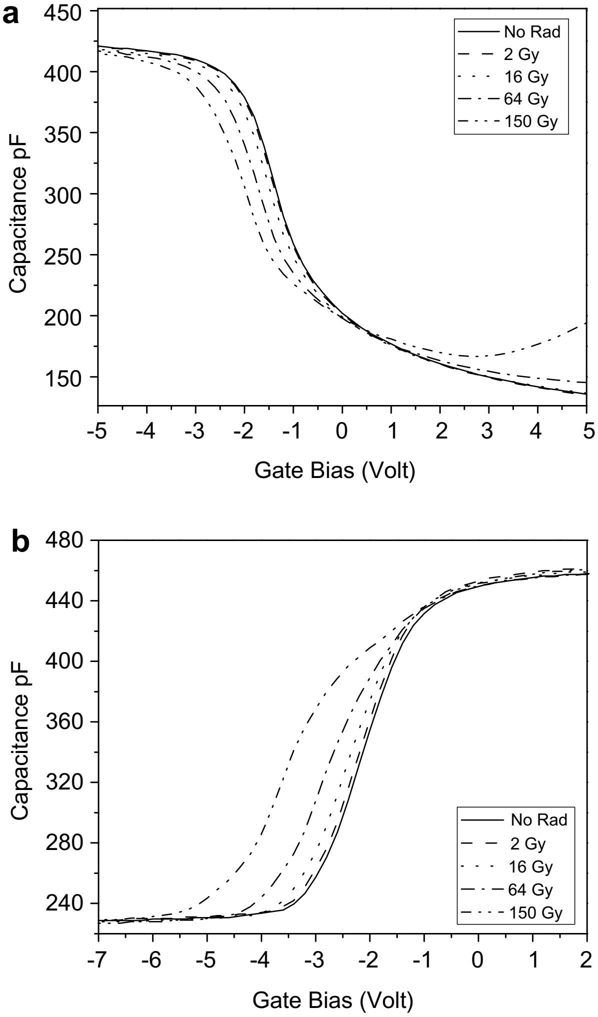

Fig. 3. *C–V* Curves for capacitors irradiated to gamma radiation (a) p-type substrate and (b) n-type substrate.

3.3. Dependence on bias

MOS device response to ionizing radiation is controlled primarily by defect generation and gate bias during exposure. The radiation induced defects which have the largest impact on MOS response are oxide-trapped charges and interface traps. The amount of oxide-trapped charges and interface traps is a function of gate bias during exposure [23,24]. However, as discussed above, the role of interface states and fixed oxide charges is not easily distinguishable. Electron–hole pairs created by the incident radiation can recombine more efficiently at low gate bias during exposure. This recombination decreases with larger gate bias during exposure. The polarity of the applied bias determines the direction of electron's motion after ionization [25]. Negative bias applied to the gate sweeps the electrons toward the interface where the recombination of electron-trapped holes is enhanced. This decreases net oxide-trapped charge and leads to less sensitivity of the MOS device under negative bias.

The variation of the radiation induced charge with negative and positive bias is shown in Fig. 5 for p- and n-type substrates. A positive and negative bias of 10 Volts has been applied to the gates for both sample types. In general, the flat band voltage shift increases with applied bias, as expected. The shift is greater for a positive gate bias for both substrate types. The similarity in the response of n- and p-type samples suggests that charge from the substrate does not play a significant role in determining the radiation induced charge formation. On the other hand, a positive gate bias generates more charges than negative

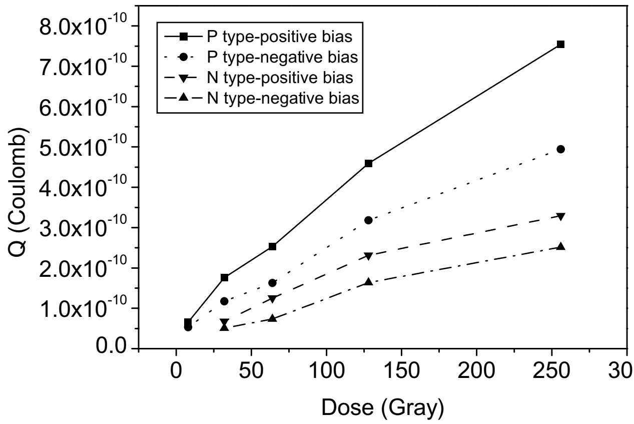

Fig. 5. Radiation induced charge versus dose for p- and n-type MOS under 10 Volt bias.

gate bias. As explained above, application of negative bias pushes the generated holes towards the SiO_2/Si interface where they can recombine with the trap holes. It is concluded that application of a positive bias to the gate is technologically more favorable if device sensitivity is important in the applications.

4. Re-usability of MOS devices

The re-usability of the device in sensor and dosimetry applications should be addressed. This is obviously related to whether or not the irradiation causes a permanent damage that cannot be repaired by a low temperature annealing process.

It is widely accepted that there are two different contributions to the flat band voltage shift, one is attributed to the oxide-trapped charges and the other is to the interface trapped-charges. Annealing causes a significant decrease in the density of these charges, showing that the charges created by radiation can be removed by an easy neutralization process that is enhanced by a low temperature annealing. One of the possible mechanisms might be heat-assisted tunneling of electrons from the substrate into the trapped positive charges in the oxide.

We repeated the irradiation/annealing cycle 9 times to observe whether the devices lose their sensing behavior with ionizing radiation. Fig. 6 shows the flat band voltage of the MOS capacitors with number of cyclic treatments. Upper dots show the flat band voltage position before the irradiation and lower ones after annealing at 200 °C under hydrogen ambient. The effect of radiation on device behavior can be reversed by annealing and this process can be repeated many times. There seems to be no indication of degrading the device operation after these 9 cycles.

5. Conclusions

We have studied the response of the MOS devices to ionizing radiation as a function of device and process parameters for sensor applications in a systematic way.

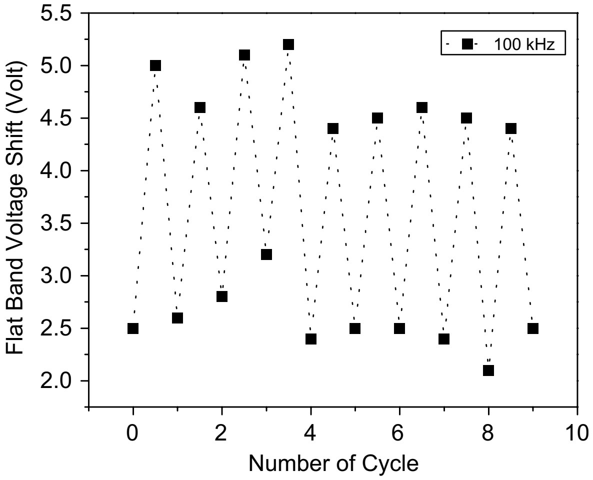

Fig. 6. Flat band voltage shift of MOS with 680 nm thickness and 1 mm diameter circular plate after irradiation and annealing treatment with zero gate bias.

The substrate type, applied bias, oxide thickness and post annealing influence the device performance in sensing the amount of radiation incident on the device. The flat band voltage shift was found to be quadratically dependent on the oxide thickness, consistent with uniform exposure and ionization through the oxide layer. p-type MOS capacitors are more sensitive than n-type ones when flat band voltage shift is used for valuation. In general, the amount of oxide-trapped charges in the oxide and interface traps generated by radiation is a function of gate bias during exposure. Application of positive bias during exposure yielded more sensitivity than negative bias. It is possible to reverse the radiation induced charging in the MOS capacitor by annealing at low temperatures. Charging/discharging proves can be repeated many times without degrading the device performance.

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