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Effect of γ-radiation on HfO_2 based MOS capacitor

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ABSTRACT

Radiation effects on Metal Oxide Semiconductor (MOS) capacitors with a HfO_2 gate insulator have been studied. Because HfO_2 is a promising high-k dielectric material for microelectronic applications, radiation effects on its performance in MOS devices is of interest. New results on radiation effects on HfO_2, particularly at low gamma radiation doses, are presented. The results are compared with other systems including those of Al_2O_3 plus silicon based Si MOS capacitors. Both devices with different gate thicknesses were irradiated with Co-60 gamma source for varying exposure time. The midgap and flatband voltage shifts in these devices were measured and analyzed. Results show that gamma radiation does not cause significant variations in the HfO_2 MOS especially at low doses.

1. Introduction

As the size of transistors continues to scale down, the use of conventional SiO_2 as a gate dielectric material is approaching physical and electrical limits. Correspondingly for advanced semiconductor technology, the transistor gate length will continue to shrink and reaches sub-20 nm by 2015 in order to achieve faster switching speed and higher device density. At the same time, gate oxide thickness is also decreasing in order to increase the gate capacitance and thus control of the gate over the channel and thickness of less than few nm will be required if silicon dioxide is used [1]. Even though many high-k materials are currently being used in microelectronics the industry is still searching for an alternative gate dielectric to SiO_2 for sub-20-nm channel length CMOS devices [2–4]. Large leakage currents can arise in these devices via direct tunneling from the substrate to the gate electrode [1,2]. By using a material with a larger dielectric constant for the gate insulator, it will be possible to build devices with an equivalent oxide thickness (EOT) of 10 nm that have significantly reduced leakage currents compared to similar devices built using SiO_2 [2,4–7]. Several "high-k" materials are being considered to replace SiO_2. A considerable amount of uncertainty still exists regarding which material can be integrated most easily into a modern CMOS process. Some of the materials under consideration are Al_2O_3, HfO_2, ZrO_2, Y_2O_3 and TiO_2 [1,2,8]. Each of these materials has advantages and disadvantages, but to date, the Group IV B metal oxides have been studied most extensively. In particular, the oxides of hafnium and zirconium appear most promising because they have relatively high dielectric constants and are the most thermodynamically stable on Si [2–5,8,9]. It has been suggested recently that high-k gate dielectrics could be developed with the concentration of Hf or Zr gradually increasing as processing techniques improve with each technology node [2].

To the best of our knowledge, only radiation effects on MOS devices with SiO_2 have been studied. Therefore it is necessary to investigate the possible radiation effects on high-k HfO_2. Here, we examine closely the radiation effects on HfO_2 capacitors and compare their responses to the response of thicker Al_2O_3 + Si. We found that HfO_2 may well be a promising candidate for future high-k dielectric materials for space applications at particularly low doses.

2. Experimental details

The MOS devices studied were capacitors fabricated on n-type and p-type silicon (1 0 0) substrates. Before the samples were put into the system, they were cleaned with a 1% HF solution for about 30 s and washed with pure water and dried with nitrogen. Many high-k dielectric materials such as Ta_2O_5, TiO_2 and STO are thermally unstable when in direct contact with Si [10]. Thus, additional passivation layers between high-k layer and Si substrate is needed to prevent interfacial reaction [11,12]. Thus, all samples are covered with hafnium metal using argon plasma and a sputtering method, after sending O_2 to the system. The base pressure before sputtering was 1.5×10^{-6} Torr and the sputtering gas pressure was 1.0×10^{-3} Torr. Afterwards, HfO_2 were grown with a Ar + O_2 plasma for about 3 min. A quasi-reactive gas mixture of Ar (98%) and O_2 (2%) was used in order to obtain the desired stoichiometry.

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Al_2O_3 + Si samples were fabricated by a co-sputtering method. The thicknesses were determined by an ellipsometer after growing. Ohmic contacts to the devices were fabricated by evaporating Al on to the back side of the wafers for n-type samples. Front electrodes to 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 range of doses, MOS samples were irradiated using a Co-60 gamma source from 0.1 to 16 Gray at a dose rate of 0.018 Gy/s. *C–V* measurements were recorded prior to and after irradiation.

3. Results and discussions

Ionizing radiation causes a shift in position of the flat band and midgap voltage of a *C–V* curve with gate voltage. These shifts were observed for low and high doses. The bidirectional shift is interesting. At high doses the shift is to the left side and at low doses the shift is to the right side, as in Figs. 1 and 2. Factors leading to the V_{fb} shift are fixed charges, interface traps, [13] and dopant diffusion. [14] However, fixed charges only cause unidirectional V_{fb} shift, since the polarity of fixed charge is unique, i.e., positive or negative. Although Lee et al. [14] reported that phosphorus diffusion into Al_2O_3 can cause V_{fb} shift, the shift is unidirectional. Onishi et al. [15] found phosphorus or boron penetration into HfO_2 also causes a bidirectional V_{fb} shift. Nevertheless, the shift directions are negative and positive with respective to the SiO_2 for phosphorus penetration in nMOS and for boron penetration in pMOS, respectively.

That is, opposite directions to our observations. Hence, we suggest the bidirectional shift in this work is not due to dopant diffusion but due to interface traps which exist at both HfO_2/Si interfaces. At low doses, acceptor-like interface states are electrically active and lead to positive flatband voltage shift. Donor-like interface states are electrically active at high doses, resulting in negative flatband voltage shift.

Figs. 1 and 2 show the shift of *C–V* curve along the voltage axis for a HfO_2 MOS device. The shifts were studied systematically for low and high doses. We observed a midgap voltage shift (ΔV_{mg}) from the *C–V* curve. The midgap voltage shift (ΔV_{mg}) caused by irradiation is only due to the oxide trapped charge [16]. Using this ΔV_{mg} value the net oxide trap-charge densities (ΔN_{ot}) can be estimated [17]

$$\Delta N_{ot} = -\frac{C_{ox}\Delta V_{mg}}{qA} \quad (1)$$

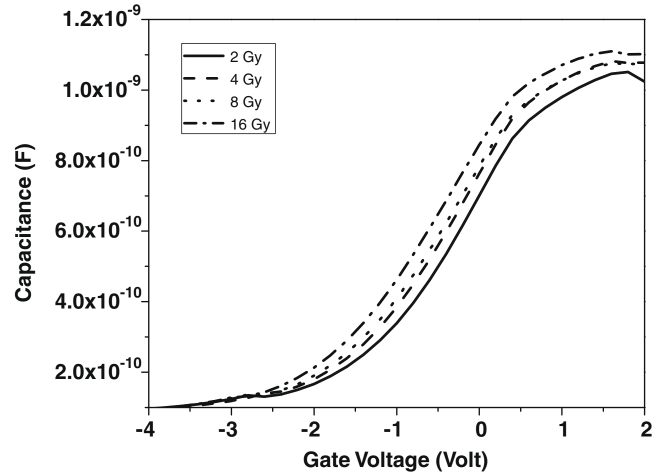

Fig. 2. *C–V* curve of HfO_2 15 nm 1 MHz from 2 Gray to 16 Gray.

where C_{ox} is the oxide capacitance measured in accumulation, $-q = (1.602 \times 10^{-19}$ C) electronic charge and *A* is the area of capacitor. From this equation, ΔN_{ot} was calculated as $\sim 2.29 \times 10^{11}$ cm^{-2} after 4 Gray and $\sim 3.38 \times 10^{11}$ cm^{-2} after 8 Gray for the HfO_2 thin film device. Afterwards the flatband voltage shift was calculated. This must take into account both the oxide trapped charge and the charge trapped on interface traps between flatband and midgap [16]. Similarly, the interface trap-charge densities (ΔN_{it}) can be estimated from the midgap-to-flatband stretch-out of the *C–V* curves by [17]

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

where C_{ox} is the oxide capacitance measured in accumulation and *A* is the area which is calculated from the radius of the mask (diameter of mask is about 0.8 mm). Using Eq. (2) we estimated ΔN_{it} to be $\sim 1.47 \times 10^{10}$ cm^{-2} after 4 Gray and $\sim 6.20 \times 10^{10}$ cm^{-2} after 8.0 Gray.

Figs. 3 and 4 show interface trap-charge density (ΔN_{it}), oxide trap-charge density (ΔN_{ot}) which increases almost linearly from 0.1 Gray to 16 Gray. After low dose irradiation, charge trapping is created. This trapped charge can be distributed in different ways [16]. There are two different contributions to the flatband voltage shift and midgap voltage shifts, one attributed to the oxide trapped charges and the other to the interface trapped charges [18]. Figs. 3 and 4 show that when the dose increases, interface and oxide

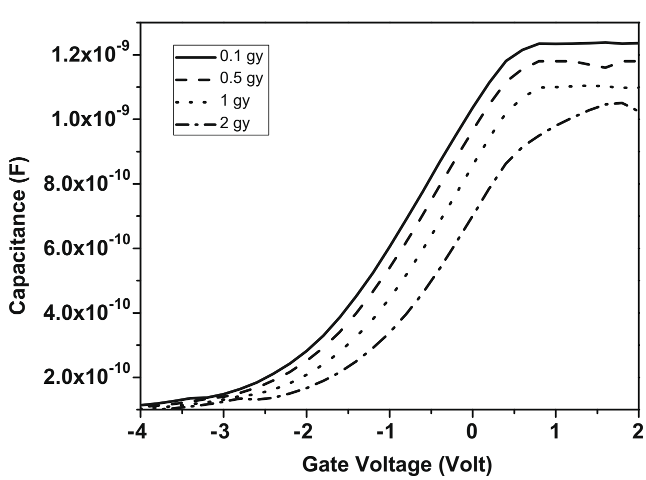

Fig. 1. *C–V* curve of HfO_2 15 nm 1 MHz from 0.1 Gray to 2 Gray.

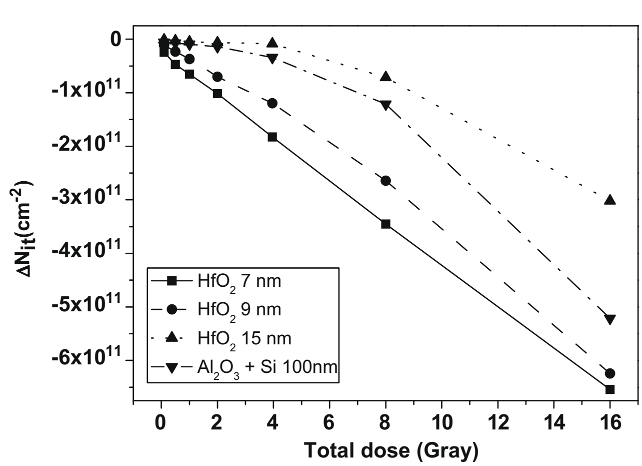

Fig. 3. Interface trap density ΔN_{it} of HfO_2 and Al_2O_3 + Si devices.

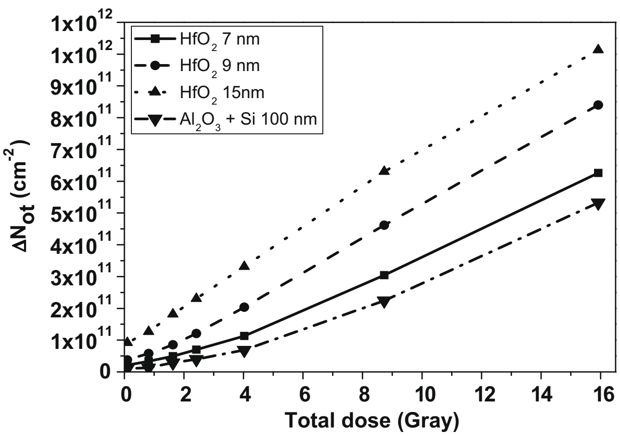

Fig. 4. Oxide trap density ΔN_{ot} of HfO_2 and Al_2O_3 + Si devices.

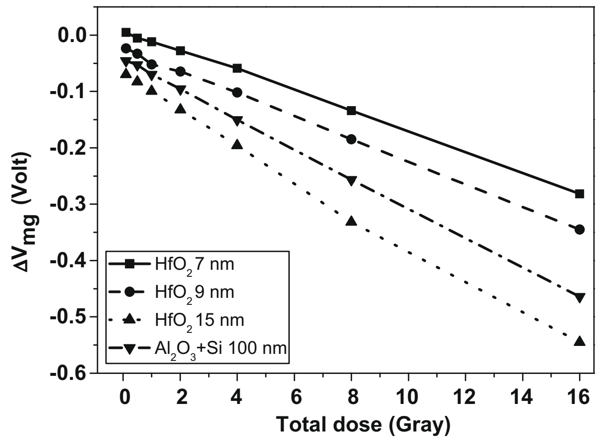

Fig. 6. Midgap voltage shift of HfO_2 from 0.1 Gray to 8 Gray.

trapped charge densities generally increase. Electrons generated during ionization disappear into the metal contact or the substrate leaving behind a hole in the oxide [19]. On the other hands, from the midgap technique, midgap voltage shift was calculated. Figs. 5 and 6 show flat band and midgap voltage shift versus total dose. The shifts change with equal dose at equal voltage shift.

Flat band voltage shifts in capacitors with HfO_2 (9, 15 nm) are greater than those with Al_2O_3 + Si (100 nm) for the same dose. It is clear that capacitors with HfO_2 gate oxide are more sensitive to gamma radiation than with Al_2O_3 + Si.

To understand the physical significance of trapped charge densities shown by Figs. 1, 2 and 5, we estimated an effective trapping efficiency for these devices [17]. Trapping efficiency is a dimensionless quantity used to approximate the intrinsic "trappiness" of the insulator [20]. The effective trapping efficiency can be estimated for alternative dielectric film using [17]

$$f_{ot} = -\Delta V_{mg}\varepsilon_{ox}/q\kappa_g f_y t_{eq} t_{phys} D \quad (3)$$

where f_{ot} is effective trapping efficiency, ΔV_{mg} is the midgap voltage shift, ε_{ox} is the dielectric constant of SiO_2 ($\sim 3.5 \times 10^{-13}$ F/cm), $-q$ is electronic charge, κ_g is the number of electron-hole pairs (EHP) generated per unit dose, f_y is the charge yield which is about 0.90 ± 0.05 (for Co-60 irradiation at 3 MV/cm) [20], t_{eq} is the equivalent oxide thickness (~2.3 nm), t_{phys} is the physical thickness of the alternative dielectric (~15 nm) and D is the total dose which is 1600 rad (16 Gray). Using Eq. (3) the effective trapping efficiency was calculated as ~15% for our HfO_2 devices. As a point of reference, net oxide trapping efficiencies for SiO_2 reported in the literature typically ranges from a few percent up to ~50%, depending primarily on the number of oxygen vacancies in the oxide. High quality radiation-hardened oxides generally exhibit trapping efficiencies of less than ~5% and this percentage decreases as the oxide quality increases [17]. The efficiency of hafnium oxide is less than three times that of SiO_2, since they have a lower defect density.

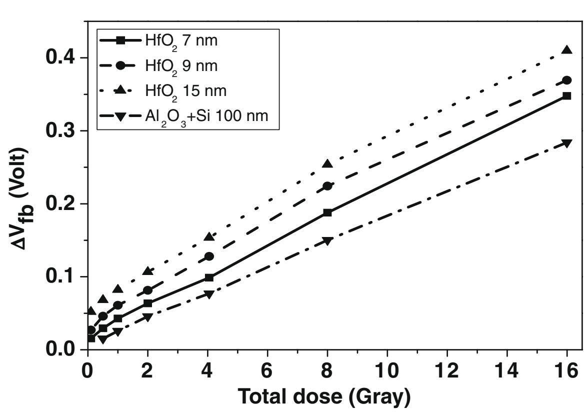

Fig. 5. Flatband voltage shift of HfO_2 and Al_2O_3 + Si from 0.1 Gray to 16 Gray.

4. Conclusions

The gamma radiation doses applied to the devices in this work are very small since technology targets values are generally about 1000 Gray for device applications. However, there are still some low dose applications and for the first time, very low dose effects on ultra thin HfO_2 were studied. Excellent dielectric properties such as high dielectric constant, low leakage current and excellent reliability were demonstrated. These results suggest that HfO_2 is a promising material for the future gate dielectric application particularly at low radiation doses.

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