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Total ionizing dose effects and annealing behaviors of HfO_2-based MOS capacitor

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With the continuously scaling down of semiconductor technology, the traditional SiO_2 as gate dielectric is approaching the physical and electrical limits. Some problems, such as the increasing leakage current and reliability issues, seriously affect the transistor performance [1]. HfO_2 has been considered to be one of the reasonable alternative solutions due to a suitable dielectric constant (about 25), the relatively large band gap (5.68 eV) and thermal stability with Si substrate [2]. High-k gate dielectric[1)] technology has been utilized for CMOS mass production below the 45 nm technology node, however the mainstream of anti-radiation CMOS technology is above 65 nm technology node. The study of the radiation effects of high-k gate dielectrics is required before the utilization of 45 nm and below technology nodes for higher integration and capacity ICs aiming at future space applications. But the publications on total ionizing dose (TID) radiation effects of HfO_2 or other high-k gate stack materials are very limited, compared with previous relevant researches on SiO_2 gate oxide. Furthermore, researchers found the component of radiation-induced interface in HfO_2-base device contains two defects: O_2^- and Hf^{+3}, which is more complex and quite different from that of traditional SiO_2-based transistor [3]. So detailed research work is still required before the wide application of this technology in harsh environment.

In this article, the effects of Gamma ray radiation and following annealing on HfO_2-based MOS capacitors have been investigated. CV hysteresis characteristics were measured at different radiation doses. $\Delta V_{\rm fb}$ (flatband voltage shift) and $\Delta V_{\rm mg}$ (midgap voltage shift) were extracted to calculate $\Delta N_{\rm ot}$ (oxide trap density variation) and $\Delta N_{\rm it}$ (interface traps density variation).

Experiment. Silicon (100) substrate with P-type doping concentration of 1×10^{15} cm^{-3} was used to fabricate the HKMG MOS capacitors (MOSCAPs). After standard clean process, silicon wafer was treated with buffered oxide etchant (BOE) to remove nature oxide. SiO_x was grown on the wafer surface using O_3 chemical oxidation. HfO_2 high-k dielectric was then deposited onto the SiO_x buffer layer by atomic layer deposition (ALD) and treated by post deposition annealing (PDA) using rapid thermal annealing (RTA) at 450°C in N_2 ambient. TiN/W metal gate was then deposited on the high-k dielectric by ALD and patterned by dry etch using BCl_3+SF_6 mixed gas. Finally, all samples were metallized with Al(Si) on backside at 380°C in N_2 ambient for 40 min. High frequency (1 MHz) CV characteristics of the MOS capacitors were measured using Keithley

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The authors declare that they have no conflict of interest.
1) https://en.wikipedia.org/wiki/High-k_dielectric.

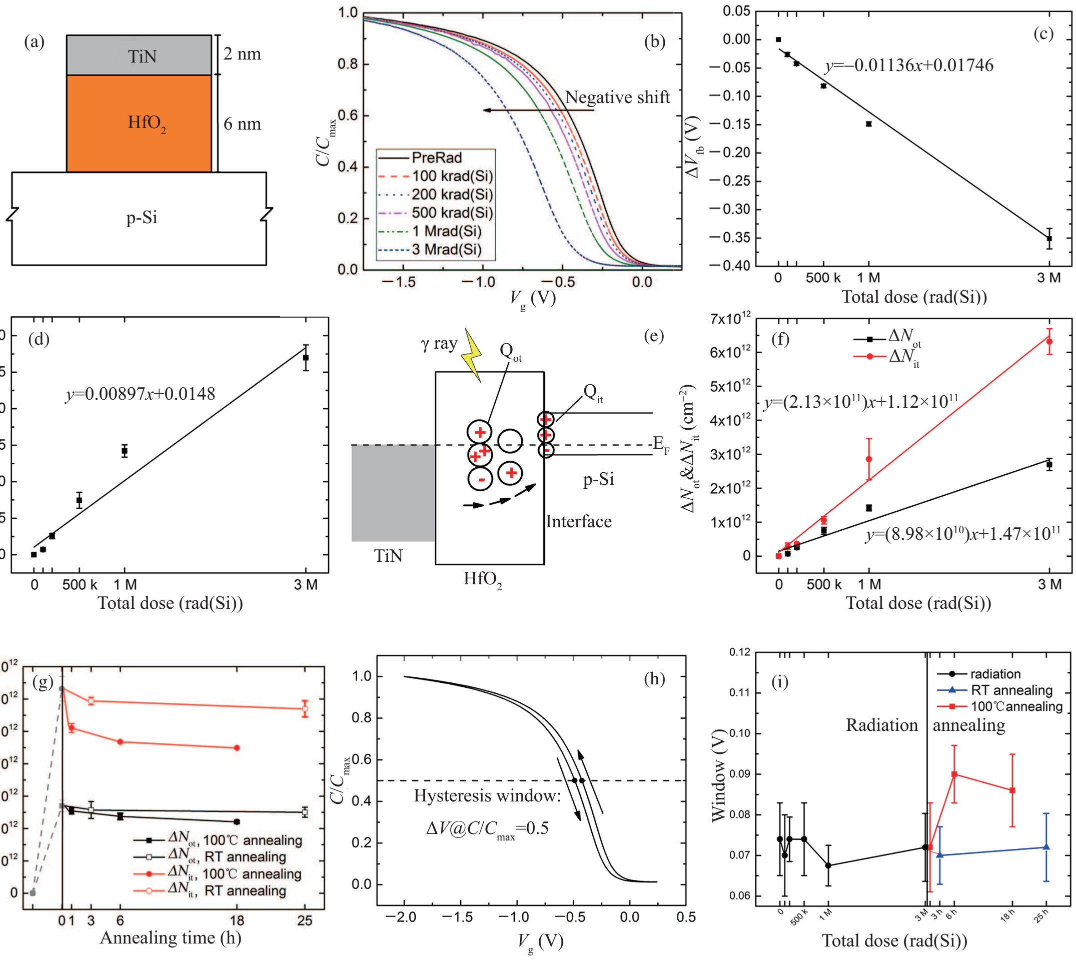

Figure 1 (Color online) (a) Illustration of the capacitor structure (not to scale); (b) 1 MHz CV characteristics of HfO_2 MOS capacitor; (c) ΔV_{fb} shifts; (d) ΔV_{mg} shifts; (e) the generation process of Q_{ot} and Q_{it} under γ ray irradiation; (f) ΔN_{ot} and ΔN_{it} of HfO_2 devices; (g) RT and 100°C annealing behaviors after irradiaion; (h) hysteresis window of HfO_2; (i) hysteresis window after radiation and following annealings.

4200 Semiconductor Parameter Analyzer. The V_{fb} and V_{mg} were extracted by fitting the measured CV data to CV simulation results by program from UC Berkeley including the quantum mechanical effect. Figure 1(a) shows the illustrated structure of the capacitors. The un-packaged capacitors samples were irradiated by a ^{60}Co Gamma source from 100 krad(Si) to 3 Mrad(Si) at a dose rate of 50 rad(Si)/s without electrical bias.

Results and discuss. Figure 1(b) shows the CV curves before and after irradiation with different doses. With the increasing dose, the curves shift towards negative direction and the gradient of the depletion region becomes smoother. ΔV_{fb} as the function of radiation dose is given in Figure 1(c). ΔV_{fb} decreases from -0.08 V at 500 krad(Si) to -0.15 V at 1 Mrad(Si) and -0.35 V at 3 Mrad(Si). A good linear relation between ΔV_{fb} and radiation dose has been found. ΔV_{mg} is presented as the lateral broadening of depletion region on CV curves. The extracted ΔV_{mg} values are 0.08 V at 200 krad(Si), 0.14 V at 1 Mrad(Si) and 0.26 V at 3 Mrad(Si) respectively as shown in Figure 1(d).

The essence of TID radiation induced damages in gate dielectric is the radiation induced net oxide trap-charge (ΔQ_{ot}) and the interface trap-charge (ΔQ_{it}). Figure 1(e) shows the generation process of ΔQ_{ot} and ΔQ_{it}. When devices were exposed to ^{60}Co source, a large number of electron-hole (e-h) pairs were created. Most of electrons escaped from metal gate because of its high mobility while holes were trapped. With the increasing dose, positive trap charges accumulated in oxide bulk or Si/HfO_2 interface. Using the value of ΔV_{mg}, ΔN_{ot} can be estimated by

$$\Delta N_{ot} = -\frac{C_{ox}\Delta V_{mg}}{qA},$$

where C_{ox} is the oxide capacitance measured in accumulation, $-q$=(1.602×10^{15}C) is the electronic charge, and A is the capacitor area. Similarly, $\Delta N_{\rm it}$ can be estimated from the midgap to flat-band stretch-out of the CV curves by

$$\Delta N_{\rm it} = \frac{\Delta V_{\rm fb} - \Delta V_{\rm mg}}{qA}.$$

The calculated $\Delta N_{\rm it}$ and $\Delta N_{\rm ot}$ are given in Figure 1(f). Trapping efficiency ($f_{\rm ot}$) is a dimensionless quantity used to approximate the intrinsic "trappiness" of the insulator [4].

The effective trapping efficiency can be estimated for alternative dielectric film using [4]

$$f_{\rm ot} = -\Delta V_{\rm mg}\varepsilon_{\rm ox}/q\kappa_{\rm g} f_{\rm y} t_{\rm eq} t_{\rm phys} D,$$

where $f_{\rm ot}$ is effective trapping efficiency, $\Delta V_{\rm mg}$ is the midgap voltage shift, $\varepsilon_{\rm ox}$ is the dielectric constant of SiO_2 (3.5×10^{13} F/cm), $-q$ is electronic charge, $\kappa_{\rm g}$ is the number of electron-hole pairs (EHP) generated per unit dose, $f_{\rm y}$ is the charge yield which is about 0.90 ± 0.05 (for ^{60}Co irradiation at 3 MV/cm), $t_{\rm eq}$ is the equivalent oxide thickness, $t_{\rm phys}$ is the physical thickness of the alternative dielectric and D is the total dose which is 3 Mrad(Si). We estimated the $f_{\rm ot}$ of HfO_2 device is 5.7%, 10 times better than SiO_2 (up to 50%, depending on the number of oxygen vacancies in the oxide) [4], which means very good irradiation resistance.

After 3 Mrad(Si) irradiation, annealing experiments on these HfO2-based capacitors under room temperature (RT) and 100°C were conducted. Figure 1(g) shows $\Delta N_{\rm ot}$ and $\Delta N_{\rm it}$ as functions of annealing time and temperature. From Figure 1(g) we can see that annealing process can partly recover TID radiation-induced damages. The higher the temperature is, the faster the devices will recover, while the irradiated device can hardly revert to its original state in a reasonable time range. According to thermal emission annealing model [5], more deep energy level trapped holes can be annealed beyond 100°C, so the annealing effect is more obvious surpassing that point.

Furthermore, the TID radiation effect on hysteresis characteristics of the HfO_2-based capacitor is also studied. Due to the "slow states" cannot follow the scanning voltage change, there will be a hysteresis curve, as Figure 1(h) shows. Figure 1(i) shows the experiment data with 5 samples. In the radiation process, the hysteresis window is almost constant. But it increased by 0.18 V (about 25%) after 6-hour annealing at 100°C. It may be caused by latent trap buildup (LITB) [6] . With the annealing time increasing, the slow-state interface traps first build up and decrease after a while. LITB depends strongly on the temperature and it is suppressed at RT.

Conclusion. In conclusion, this article discusses the TID induced radiation damages on HfO_2-based capacitor and the annealing effects on it. Compared with the negative interface reported in the past [4], we found positive $Q_{\rm ot}$ and $Q_{\rm it}$ increase with the total dose, while the trapping efficiency is much lower than SiO_2. The results show that HfO_2 has good irradiation resistance for space applications.

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