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The Co-60 gamma-ray irradiation effects on the Al/$HfSiO_4$/p-Si/Al MOS capacitors

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ABSTRACT

In this work, the initial interface trap density (N_{it}) to examine device compability for microelectronics and then the Co-60 gamma irradiation responses of Al/$HfSiO_4$/p-Si/Al (MOS) capacitors were investigated in various dose ranges up to 70 Gy. Pre-irradiation response of the devices was evaluated from high frequency (HF) and low frequency (LF) capacitance method and the N_{it} was calculated as 9.91×10^{11} cm^{-2} which shows that the $HfSiO_4$/p-Si interface quality is convenient for microelectronics applications. The irradiation responses of the devices were carried out from flat-band and mid-gap voltage shifts obtained from stretch of capacitance characteristics prior to and after irradiation. The results show that the flat band voltages very slightly shifted to positive voltage values demonstrating the enhancement of negative charge trapping in device structure. The sensitivity of the Al/$HfSiO_4$/p-Si/Al MOS capacitors was found to be 4.41 mV/Gy for 300 nm-thick $HfSiO_4$ gate dielectrics. This value approximately 6.5 times smaller compared to the same thickness conventional SiO_2 based MOS devices. Therefore, $HfSiO_4$ exhibits crucial irradiation tolerance in gamma irradiation environment. Consequently, $HfSiO_4$ dielectrics may have significant usage for microelectronic technology as a radiation hard material where radiation field exists such as in space applications.

1. Introduction

Irradiation influences on the electrical characteristics of metal--oxide-semiconductor (MOS) based devices and relevant technologies are complex in nature and change much depending on basic device characteristics including the package types of devices, operation temperatures etc. (Kahraman et al., 2015a; Tugay et al., 2012). Electronic devices used in markets can contain numerous types of dielectric materials. Silicon Dioxide is the conventional dielectric layer but it has limiting performance for advance microelectronic technology due to high tunnelling current effects under certain oxide thickness. Hence, new high-k materials have been studied to replace to SiO_2 layer for technological applications. It has been reported that HfO_2 and Al_2O_3 are most popular promising two gate dielectrics for microelectronics. Nevertheless, HfO_2 and Al_2O_3, device characteristics have been much effected under radiation environments (Ergin et al., 2010; Yilmaz et al., 2008). Ionizing radiation generates significant charge in these dielectrics leading to device degradation (Anjum et al., 2016; Candelori et al., 1999; Petr and Gilar, 1985). Hence, explorations of radiation resistivity of new high-k materials are important for the devices applications used in high irradiation field areas such as space and nuclear applications (Arinero et al., 2011). Together with the reported high- k materials such as HfO_2, Al_2O_3, etc (Kahraman et al., 2015b; Kaya and Yilmaz, 2014a), Halfnium silicate ($HfSiO_4$) also appears to be the most promising good dielectric material, with high dielectric constants, excellent thermal stability on Si (Felix et al., 2002), and good radiation tolerance $HfSiO_4$ under x-ray radiation environment (Felix et al., 2002). A number of irradiation types affect the devices used in space and nuclear applications. Thus, their possible effects in the device electrical characteristics should be entirely studied for specifying device performance under various radiation fields. Therefore, in this work, we have investigated initial electrical characteristics and gamma radiation response of Al/HfSiO4/p-Si (MOS) capacitors. The main purpose of this study is to examine the behaviour of the Al/$HfSiO_4$/p-Si/Al under the gamma radiation. In addition, $HfSiO_4$ dielectric material is an alternative to traditional dielectric materials, whose electrical properties are deformed by radiation even at low doses.

The initial interface trap density was calculated from measured capacitance–voltage (C–V) curves by using high (1 MHz) and low (50 kHz) frequency capacitance method to specify $HfSiO_4$/p-Si interface quality and compability of device on microelectronics. The details of electrical compability of the fabricated devices can be seen in our

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previous work (Lok et al., 2016). After that, the Co-60 gamma irradiation effects on the device characteristics were determined from the mid-gap and flat-band voltage shifts of capacitance curves measured at 1 MHz up to 70 Gy.

2. Experimental details

In order to fabricate the $HfSiO_4$ thin films, a p-type (100) silicon wafer with 500 µm thick and 1–4 Ω resistivity, was cleaned by following the standard Radio Corporation of America (RCA) cleaning process. The cleaned wafer was loaded in the chamber of the sputter system. The base pressure of the chamber was below 4.0×10^{-4} Pa. $HfSiO_4$ target with dimension 4-in. and purity of 99.99%, was used for the deposition of the dielectric layer. Ultra–pure Ar gas (99.9999%) was used during sputtering the process. Flow rate argon gas was kept at 16 sccm. Before commercial deposition, the pre–sputtering was done for 3 h at 300 W in order to get rid of any impurities on the target surface at 1 Pa. Following this step, commercial sputtering was performed under same parameters for 30 min. The thickness of the deposited films was measured as 300 nm using the spectroscopic reflectometer. The deposited films were annealed at 750 °C for 40 min in the Nitrogen ambient. Al/$HfSiO_4$/p-Si/Al (MOS) capacitors were fabricated from annealed thin films. The front electrodes of the thin films were formed in circular dots which are made of aluminium (Al) deposited by sputtering with 1.5 mm- diameter circular shadow mask. Back omics contact, which is made of Aluminium (Al) were deposited on the backside of the films by also sputtering.

The capacitance - voltage (C-V) characteristics were measured at 1 MHz and 50 kHz to investigate the initial interface trap density and interface quality. After that, four different Al/$HfSiO_4$/p-Si/Al capacitors were irradiated at 2, 4, 6, 12, 36, 50 and 70 Gy using GAMMACELL 220 Co-60 Radioactive Source with a dose rate of 5,56 mGy/s located in the department of chemistry, Middle East Technical University in Turkey. During the irradiation, samples were irradiated continuously and cumulative doses were given up to 70 Gy. These MOS capacitors were irradiated at a distance of about 20 cm and were centred with respect to irradiation at room temperature. Besides, the decay of a Co-60 nucleus releases two gamma quanta with energies of 1.173 MeV and 1.332 MeV. The C-V of each irradiated MOS capacitors was measured immediately within 5 min to avoid fading. The same procedure was applied for each step. The C–V measurements were performed prior to and after irradiation at high frequency (1 MHz) by using an Impedance Analyzer (MODEL HIOKI 3532-50 LCR meter). The measured complete C–V characteristics under various gamma irradiation doses were given for one capacitor, while the changes in the parameters for both four measurements were placed in error bars for the other figures

3. Results and discussion

The initial interface trap density (N_{it}) which varies by the fabrication process is a crucial parameter to specify device compatibility for microelectronics. Hence, we firstly calculated the initial interface trap density before the irradiation response of $HfSiO_4$ dielectric. Several methods have been used to calculate the N_{it} of the conventional MOS capacitors (Ergin et al., 2010; Kaya et al., 2014; Nicollian and Brews, 2003; Tecimer et al., 2014; Yilmaz et al., 2008). Among them, the high and low frequency capacitance method is accurate and easiest one to calculate N_{it}. Hence, capacitance characteristics of Al/$HfSiO_4$/p-Si/Al capacitors measured at high (1 MHz) and low (50 kHz) frequencies and results are shown in Fig. 1. It is seen that the capacitance curve shifts to more positive voltage in low frequency measurement due to time dependent charges. In addition, the N_{it} was determined by the following equation (Tataroglu and Altindal, 2008)

$$qAN_s = N_{it} = \left(\frac{1}{C_{HF} - C_{OX}}\right)^{-1} - \left(\frac{1}{C_{LF} - C_{OX}}\right)^{-1} \quad (1)$$

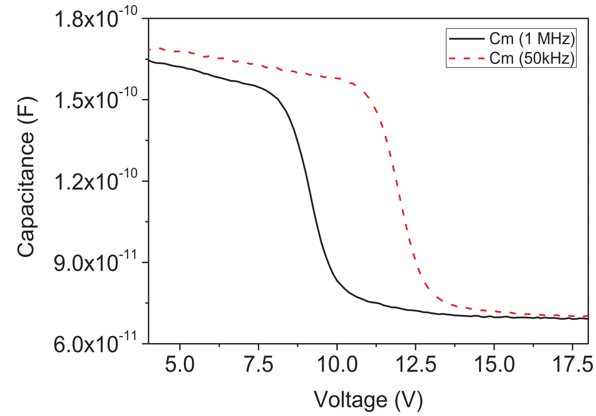

Fig. 1. The capacitance – voltage characteristics of Al/$HfSiO_4$/p-Si/Al capacitors measured at high (1 MHz) and low (50 kHz) frequencies.

where C_{HF} and C_{LF} are high and low frequency capacitance, respectively. A is capacitor area, C_{ox} is oxide capacitance whose value is $1{,}04 \times 10^{-9}$. Using Eq. (1), the N_{it} value was found as $9{,}91 \times 10^{-11}$ $eV^{-1}cm^{-2}$. This calculated N_{it} value is in accord with reported electrical characteristics for MOS based technology (Castagne and Vapaille, 1971; Dokme and Altindal, 2007). Other important features of the Al/$HfSiO_4$/p-Si/Al capacitors can be investigated by our previous study (Lok et al., 2016).

Ionizing radiation may create defects which are interface traps and the oxide traps in the metal oxide semiconductor devices. These defects affect electrical characteristics of MOS based devices (Kaya and Yilmaz, 2014b). The ionizing radiation gives rise to shift in the position of the flat band voltage of the C–V curve along the voltage axis due to variation of total trapped charge density generated by irradiation (Yilmaz et al., 2007). The conventional capacitance- voltage characteristics of devices are delicate tools to investigate the irradiation effects on the electrical characteristics of MOS based devices. Thanks to the flat band and mid gap voltage shift, change of interface trapped charge density and change of the oxide-trapped charge densities can be determined. Hence, after exposing to different levels of the gamma-radiation dose, the capacitance–voltage (C–V) characteristics of the Al/$HfSiO_4$/p-Si/Al capacitors were measured at considerable high frequency (1 MHz) to eliminate contribution of the parasitic effects of interface state in the measured capacitance. The equivalent capacitance circuit can be seen in Fig. 2(a) and (b) for non-irradiated samples and after irradiation, respectively. As seen in Fig. 2(a), the interface-trap lifetime (τ), which is expressed as a product of resistance associated with interface states (R_{it}) and interface state capacitance (C_{it}), is approximately 10^{-7} s in the literature (Gong et al., 2009; Kahraman et al., 2015b). At the high frequencies (even 500 kHz >), applied voltage frequencies are higher than the lifetime frequency of the interface states ($1/\tau$). Hence, interface states are not fast enough to rearrange in response to the applied voltage excitation. Therefore, the interface states contribution to the total capacitance is almost zero.

The measured C–V curves of the Al/$HfSiO_4$/p-Si/Al capacitors before and after the gamma-irradiation are depicted, respectively, in Fig. 3. We have observed that, the C–V characteristics of the Al/$HfSiO_4$/p-Si/Al capacitors shift toward more positive voltages with increasing the radiation dose. During the irradiation process, enormous numbers of electron and hole pairs are generated in oxide layer. Some of these charges, which escaped from the initial recombination, were trapped by defects in the oxide layer and oxide/semiconductor interface (Kaya and Yilmaz, 2014b). Depending on the sing of the trapped charges, flat band voltage can shift to either right or left.

The electrons are much more mobile than the holes. So, most probably expected result is that the positive charges are trapped in the device structure leading to negative flat band/ midgap voltage shift (Knoll, 2000). In contradistinction to this, the C–V characteristics of the

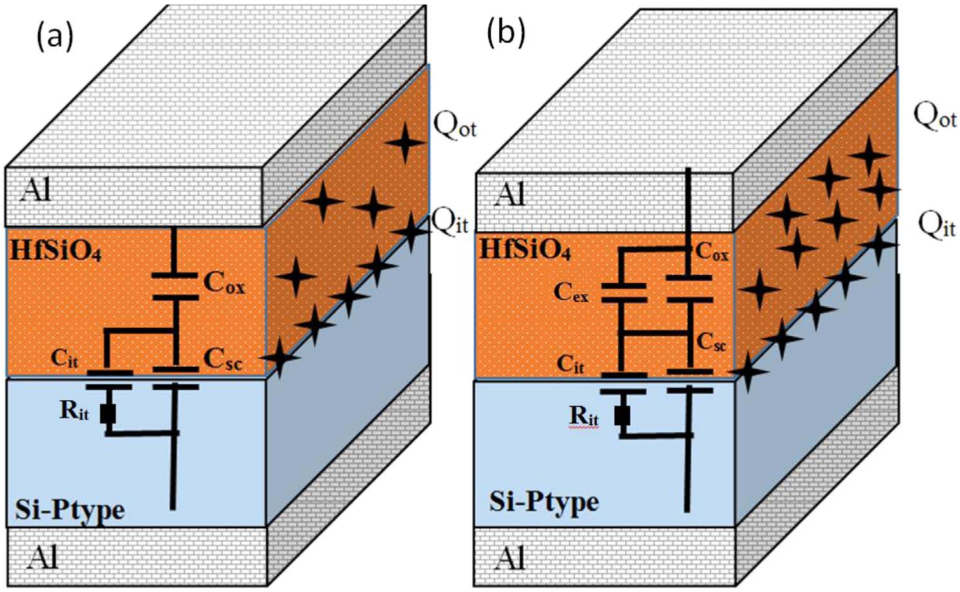

Fig. 2. The equivalent capacitance of the total capacitance (a) before irradiation and (b) after.

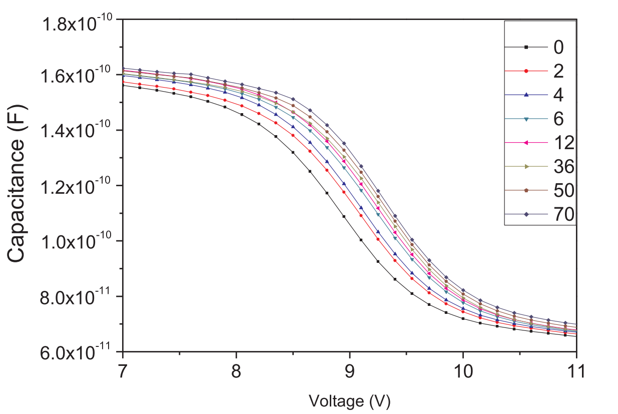

Fig. 3. C–V curves of Al/$HfSiO_4$/p-Si/Al capacitors before and after gamma irradiation at different doses.

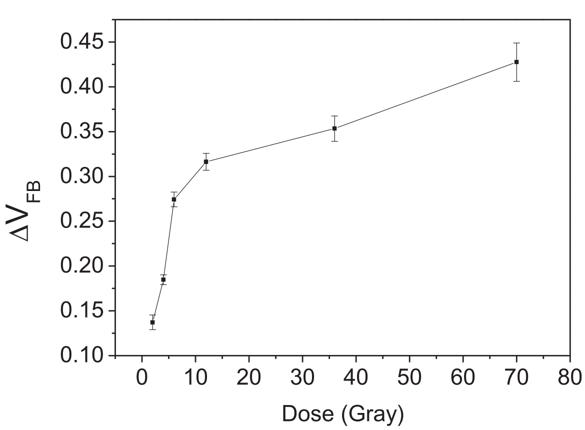

Fig. 4. Flat band voltage shift of Al/$HfSiO_4$/p-Si/Al capacitors from 2 to 70 Gy.

Al/HfSiO4/p-Si (MOS) capacitors show that flatland and mid gap voltages shift toward positive values. This indicates the negative charges are trapped in the devices structure of the Al/$HfSiO_4$/p-Si (MOS) capacitor. On the other hand, capacitance values slightly increase with increasing radiation dose as seen in Fig. 3. There are two possible reasons, which affect the increased capacitance. The first possible reason may be the contribution of generated interface states and/or border trap densities to measured capacitance (Kaya et al., 2015; Tataroglu and Altindal, 2006). The second reason could be that the radiation may passivate the trap densities in the device. This leads to rise in the capacitance characteristics (Ma and Dressendorfer, 1989). The dominant effect in the rise on the capacitance is going to be discussed further. In addition, the flat band voltage shift with respect to the given doses gives the sensitivity of the dielectric layer, which is also important knowledge for the usability of the MOS based devices in the radiation environment either as a dosimetric purpose or as resistive materials to irradiation. Therefore, the flat band voltage changes with respect to the given dose curves of the Al/$HfSiO_4$/p-Si/Al capacitors as shown in Fig. 4. It is clearly visible in Fig. 4 that a deviation of at most 5% was observed in the error bars for the flat band voltage variation. A margin of error of 5% can be accepted. The response of these devices shows linearity from 2 to 12 Gy. But, the linearity is degraded after 12 Gy. Additionally, it has been also observed that the flat band voltage shift is very small for the Al/$HfSiO_4$/p-Si/Al capacitors compared to SiO_2 based devices (Felix et al., 2002). The sensitivity of devices obtained from the flat band voltage shift is 4.41 mV/Gy for 300 nm thick Al/$HfSiO_4$/p-Si/Al capacitors. This value is 41 mV/Gy for non-biasing 400 nm-thick SiO_2 (Pejovic, 2015). The sensitivity for the SiO_2 layer is proportional to square of the oxide thickness (Pejovic, 2015). Hence, the sensitivity of SiO_2 layer, having 300 nm that is the same gate oxide thickness as studied Al/HfSiO4/p-Si/Al capacitors is nearly 28 mV/Gy. Comparing these values, it is seen that $HfSiO_4$ dielectrics approximately 6.5 times insensitive than conventional SiO_2 layer. Consequently, Al/$HfSiO_4$/p-Si/Al capacitors does not a give good linearity and it is relatively insensitive to used MOS based radiation measurement devices, such as RadFETs etc. However, although it has acceptable capacitance rise up on irradiation, it may have important usage as radiation hard materials.

The radiation induced trapped charges in the oxide (ΔN_{ot}) were determined from the mid-gap voltage shifts due to the interface states which are expected to be neutral at mid-gap level and would not contribute to the mid-gap voltage shift. The ΔN_{ot} densities can be calculated by the following equation (Kahraman and Yilmaz, 2017; Kaya and Yilmaz, 2014b)

$$\Delta N_{ot} = -\frac{C_{ox}\Delta V_{mg}}{qA} \tag{2}$$

where, C_{ox} is the oxide capacitance with value of 1,04 $\times$ 10^{-9} F, q = (1.602 $\times$ 10^{-19} C) is electric charge, A is the capacitor area and ΔV_{mg} is the midgap voltage changes. From Eq. (2), ΔN_{ot} was calculated to be nearly 4.075 $\times$ 10^{11} cm^{-2} for exposed 2 Gy, and 1.282 $\times$ 10^{12} cm^{-2}

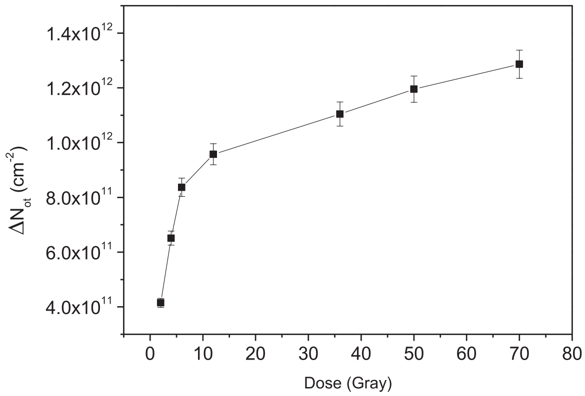

Fig. 5. Radiation induced oxide trap density, ΔN_{ot}, of Al/$HfSiO_4$/p-Si/Al capacitors.

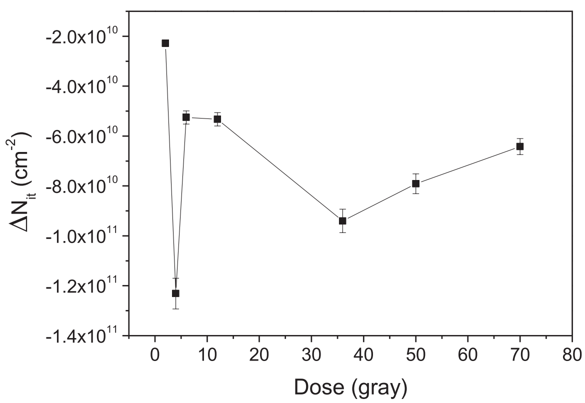

Fig. 6. Radiation induced interface trap density, ΔN_{it}, of Al/$HfSiO_4$/p-Si/Al capacitors.

after the exposed 70 Gy respectively.

The radiation induced interface trap density (ΔN_{it}) was calculated by the following equation (Kahraman and Yilmaz, 2017; Kaya and Yilmaz, 2014b)

$$\Delta N_{it} = -\frac{C_{ox}(\Delta V_{fb} - \Delta V_{mg})}{qA} \tag{3}$$

where C_{ox} is the oxide capacitance, q is the electric charge, and A is the capacitor area. ΔN_{it} is approximately $-2.28 \times 10^{10}\,cm^{-2}$, $-6.41 \times 10^{10}\,cm^{-2}$ after the radiation 2 and 70 Gy respectively for the Al/HfSiO4/p-Si (MOS) capacitor.

The distribution of calculated ΔN_{ot} and ΔN_{it} values of the Al/$HfSiO_4$/p-Si/Al capacitors are shown in Figs. 5 and 6. Comparing these two figures, each shows different behaviours. It can be seen in Fig. 5 that there is almost linearly an increase from 2 to 12 Gy for the ΔN_{ot}. This means that the ΔN_{ot} in the oxide layer increased. On the other hand, density of interface state response is very confusing. When the Al/$HfSiO_4$/p-Si/Al capacitors was irradiated first time for 2 Gy, density of the interface state increased, dramatically. The first response might have been with a splash of radiation. After that, it is decreased from 2 to 4 and 36–70 Gy. This behaviour is due to passivation. The passivation of the dielectric layer shows different behaviour for different exposed doses (Kaya and Yilmaz, 2014b). The radiation breaks the bond in the device structure, however, some time it may also give energy, like annealing, to un-bounded atoms, i.e., Si, Hf or O herein, to make new chemical bonds. Hence, it decreases the trap densities as seen in Fig. 6. So, the behaviour of interface state density from 2 to 4 and from 36 to 70 Gy is attributed to the passivation of the dielectric/semiconductor interfaces. In addition, these results have demonstrated that the total charge is enhanced in the device structure due to irradiation effects explained herein before. However, the calculated charge densities are still in order of 10^{11}–$10^{12}\,cm^{-2}$. These values are still are acceptable for MOS devices used in the microelectronic. On the other hand, it has been observed that the oxide-trapped charges are constantly enhanced with irradiation similar to capacitance values. It is well-known that the trapped charges in oxide bulk layer does not sensitive to the applied voltage frequency and also does not affect the capacitance value. However, the border traps (also known as switching oxide traps) located in the very close interface may act like interface traps. Therefore, these border traps may cause deviations in the electrical characteristics (Fleetwood, 1992; Frohlich et al., 2013; Jaksic et al., 2002; Pejovic, 2015). The possible effects of border trap capacitance, C_{ex}, on the measured capacitance can be seen in Fig. 2(b). It has been also found from our previous study, the border traps are effective in the $HfSiO_4$/p-Si interface (Lok et al., 2016). In addition, the passivation and interface trap density do not exhibit stable trend with irradiation exposure. The rise in the capacitance characteristics is due to the generation of border traps.

4. Conclusion

The effects of gamma-ray irradiation on the Al/$HfSiO_4$/p-Si/Al capacitors have been analysed in this study. The initial interface strap density caused by fabrication was found to be 9,91 $\times$ $10^{-11}\,eV^{-1}\,cm^{-2}$ by using HF-LF capacitance method which is suitable for MOS based devices. It is observed that irradiation slightly rise the capacitance characteristics of device and also cause the flat band voltages shift toward more positive voltages due to generation trap centres and electron trapping on the device structure. In addition, the numbers of oxide trap charges are generated much more than interface trap charges. So, oxide trap charges are more effective comparing to the interface trap charges for the flat band voltage shift in $HfSiO_4$. Comparing the changes of electrical characteristics of Al/$HfSiO_4$/p-Si/Al capacitors with conventional SiO_2 based devices, it has seen that $HfSiO_4$ based devices are more insensitive to irradiation. Hence, one may conclude that hafnium silicate can be a good radiation-hardened dielectric material in the future applications where high irradiation field exist such as nuclear reactors and space.

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