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GAMMA IRRADIATION RESPONSE ON SINWs BASED MOS CAPACITOR WITH HIGH-K Yb_2O_3 GATE DIELECTRIC

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Abstract. *The investigations of gamma irradiation response on silicon nanowires (SiNWs) based MOS capacitor with high- k of Yb_2O_3 is very important in the fields of semiconductors physics and nanotechnology. Hence, in this current work, we fabricated SiNWs using metal assisted chemical etching (MACE) technique and then Al/Yb_2O_3/SiNWs/n-Si (100)/Al MOS capacitor was exposed to gamma rays using Co-60 source at different doses of 0-4Gy, respectively. Our experimental results demonstrated that the capacitance value in the accumulation region decreased with increasing in the radiation dose, while the C-V curves shifted toward negative voltage side. In addition, the interface states density (D_{it}) increased with an increase in the gamma irradiation exposure. The value of D_{it} was found in the range of 6.98×10^{09} eV^{-1} cm^{-2} and 1.14×10^{10} eV^{-1} cm^{-2}.*

Keywords: *SiNWs, MACE, MOS capacitor, gamma irradiation, C-V, G/ω-V*

1. Introduction

Metal oxide semiconductor (MOS) devices have attracted research interests from various research communities in the last decades and have been integrated them in various fields such as radiation sensors, electronic devices, and nanotechnology [1]–[3]. The existence of oxide layer in MOS devices makes them very sensitive to radiation. Most cases the radiation induced damage occurs at the oxide/semiconductor interface. The exposure of high energetic particles (gamma rays, heavy ions, alpha particles, and protons) to MOS devices is because of the impact on displacement and ionization that creates the free charges in the material [4]–[6]. Generally, there are four different types of oxide charges that leads to the degradation of MOS devices. These are fixed oxide-charge, oxide-trapped, mobile charge, and interface trap- charge [7]. These charges can have significant impact on the electrical characteristics of the fabricated device and resulting their degradation and applications [5], [6].

Many efforts have recently been devoted to investigating radiation response on the MOS structures using high dielectric constant materials [8], [9]. Also, the effects of gamma irradiation on structural, morphological, optical, and electrical properties of Zinc oxide (ZnO), Zinc (Zn) and Copper (Cu) nanowires [10]–[12]. For example, N. Manikanthababu *et al.* studied the gamma irradiation effect on MOS devices with HfO_2 thin films deposited by e-beam evaporation and RF sputtering techniques, respectively. They found that the capacitance value and leakage current density increased with an increase in the irradiation doses. This was due to the generation of interface trapped charges and defects after gamma irradiation exposure [13]. Moreover, Kaur and Chauhan investigated the gamma irradiation response on Zn nanowires. They found that the conductivity value of I-V measurements decreased as the irradiation dose increased, which could be attributed to an increase in the diffusive scattering of negative charges (electrons) from grain boundaries [14].

However, as far as gamma irradiation effect is concerned, there is no report in the literature about the influence of radiation on SiNWs based MOS capacitor with Yb_2O_3 as a oxide layer [15]–[17]. Therefore, it is very important to study and analyze the impact of radiation on the SiNWs based capacitors. This is due to electronic, optical, and mechanical properties of SiNWs [18], [19]. Moreover, Yb_2O_3 is a promising high-k material owing to its large energy band gap (5eV), high-k value of 14, and high sensitivity to high energetic particles (gamma rays) [16], [17], [20]. Therefore, in this research paper, the influence of gamma irradiation on the SiNWs based MOS capacitors has been discussed symmetrically. Our experimental results have been compared to those results reported by earlier studies.

2. Experimental details

The SiNWs based MOS capacitors were fabricated in this current study. The thickness of n-Si (100) wafers was 500µm and the resistivity of 2-4Ωcm. After the RCA cleaning processes, SiNWs were fabricated by using MACE method [21]. The experimental details for the fabrication of SiNWs can be found in our previous

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studies[22] Subsequently, the Yb_2O_3 thin films were deposited onto SiNWs/n-Si (100) by e-beam evaporation technique under the experimental conditions of 250 °C substrate temperature, high vacuum chamber pressure ~ 6.0×10^{-4} Pa and the current filament was increased up to 95mÅ. The thickness of Yb_2O_3 thin film was measured using Sun Spectroscopy Ellipsometry system and found to be 135nm. The wafers were then loaded in the RF magnetron sputtering technique for the formation of gate electrodes and back contact and for more details the reader is also refer to our previous work [22], [23]. The samples were annealed at 450°C for 30min under forming gas of N_2:H_2 (10:2). The fabricated SiNWs based capacitors were exposed to Co-60 gamma ray source at the dose rate of 18Gy/h without applying any external voltage at room temperature. The devices were irradiated at different doses in the range of 0-4Gy. Moreover, the C-V measurements were carried out prior to and after gamma irradiation at 1MHz. The voltage was arranged between -10V and +10V with a step voltage of 0.125V and with a help of Keithley 4200 semiconductor characterization system (SCS). Finally, Figure 1, shows schematic representation of fabricated device in this current work.

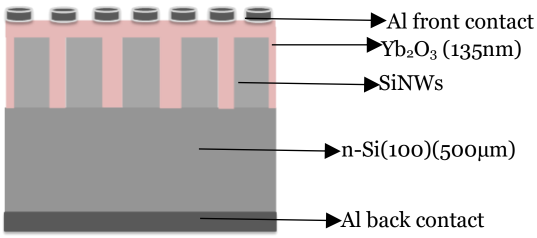

Figure 1. Structure of Al/Yb_2O_3/SiNWs/n-Si(100) MOS capacitor.

3. Results and discussion

3.1. Crystallinity, elemental, and surface morphologies analysis

The XRD patterns of the SiNWs etched for 4min and as deposited and annealed sample at 400°C for Yb_2O_3/SiNWs are given in Figure 2. In the XRD patterns of SiNWs only one Si peak is present which indexed to (400). On the other hand, we could not find any single peak for Ag, and this is due to the removal by HNO_3 during the fabrication process. Also, similar results have been reported by previous researchers[24]. Moreover, Energy dispersive X-ray spectroscopy (EDS) analysis also support these results as shown in Fig. 3(a) and (b). However, in the XRD pattern of as deposited sample, we found only two peaks for Yb_2O_3 thin films at 2θ=23.9° and 29.3° with the preferred orientation of (211) and (222). While, in the XRD pattern of annealed sample at 400°C, we also found five peaks for Yb_2O_3 thin films. These peaks located at 2θ=25.6°, 28.7°, 43.3°, 48.8°, and 57.7°, and are associated with the preferred orientation of (211), (222), (422), (440), and (622). Similar results have been reported for Yb_2O_3 thin films based on hetero junction diodes by K.S. Mohan *et al.* [25]. This indicate that annealing temperature could lead to an improvement of the crystalline structure of the thin films[26]. Moreover, these peaks were found by using the card number of ICDD 25-5792.

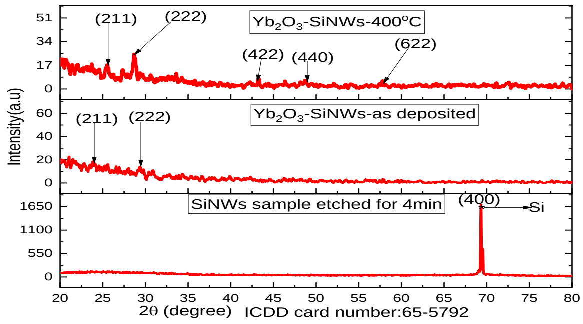

Figure 2. XRD spectra of SiNWs etched for 4min and annealed sample at 400°C for Yb_2O_3/SiNWs.

The elemental composition of SiNWs and after deposition Yb_2O_3 onto SiNWs/n-Si(100) was analyzed by EDS) technique. As may be noted from Fig. 3(a) and 3(b). There are only three elements confirms by EDS analysis and these are O, Si and Yb. In the EDS spectra oxygen has X-ray signals K_α at 0.95eV and K_α 0.98eV while silicon has K_α at 1.89eV and K_α at 1.85eV in Fig. 3(a) and (b). Ytterbium has M_α at 1.61eV, L_α at 7.76eV and L_b at 8.20eV. Moreover, there is no Ag element in all EDS spectra. This could be due to the removal of AgNPs by HNO_3 during the fabrication of SiNWs as stated before in Fig. 2.

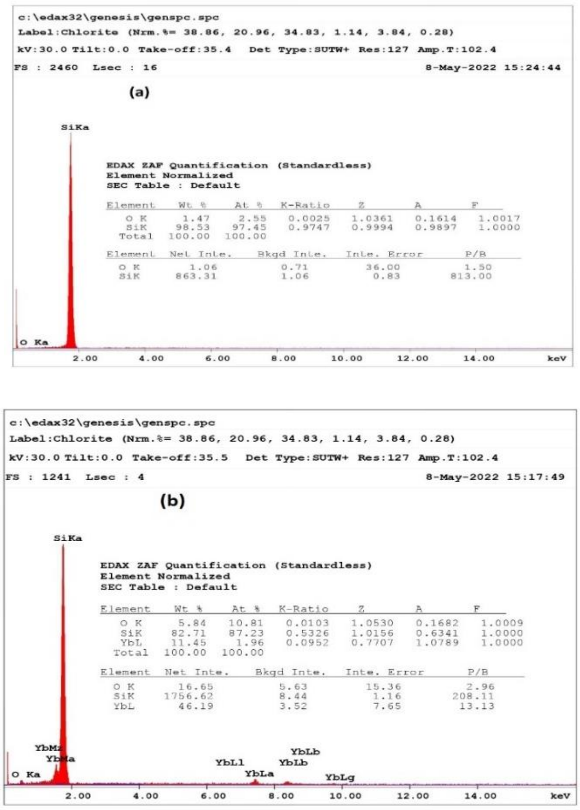

Figure 3. EDS spectra of (a) SiNWs and (b) after deposition of Yb_2O_3 onto SiNWs/n-Si(100).

Figure 4, shows the cross sectional and top view SEM images of SiNWs. It is observed that nanowires arrays are perpendicular and distributed uniformly over the surface of silicon substrates and similar results have been reported [18], [27]. However, after deposition of Yb_2O_3 thin films into SiNWs, we found that the surface morphologies of SiNWs decreased dramatically. This may be due to the penetration of Yb_2O_3 into SiNWs arrays during deposition as shown in Fig. 4(c).

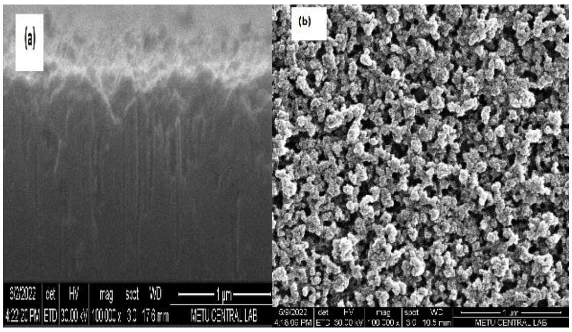

Figure 4. Cross sectional (a) and (b) top view SEM images of SiNWs.

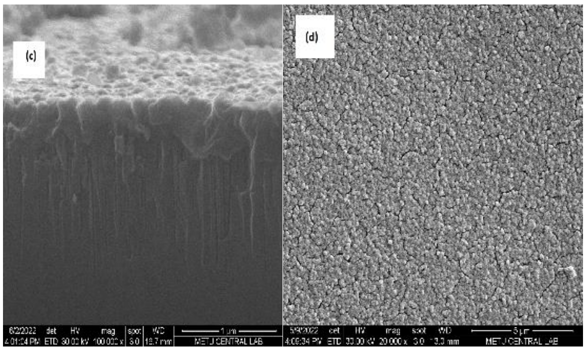

Figure 4. Cross sectional (c) and (d) top view SEM images of SiNWs after deposition of Yb_2O_3 thin films.

3.2. Gamma irradiation response on MOS capacitor based SiNWs.

Figure 5 shows capacitance-voltage(C-V) curves of Al/Yb_2O_3/SiNWs/MOS capacitor at different doses of 0-4Gy and measured at 1MHz. The aim of choosing a 1 MHz frequency in this study is to investigate and observe the high-frequency behavior of this structure. Also, it is indicated that the peak value of series resistance (Rs) decreased in this frequency [20].

As may be noted from Figure 5, the capacitance value in the accumulation region decreased with an increase in the radiation dose. We also found that there is some fluctuation in the accumulation region. This behavior of the capacitance in the accumulation could be related to the generation of various defects and trapped charges after gamma irradiation exposure [5], [6], [8], [15].

As shown in Figure 5, the C-V curves shifted toward the negative voltage side with an increase in the radiation dose. This shift is observed in the mid gap voltage (ΔV_{mg}). The shift in the ΔV_{mg} as the result of oxide trapped charges (ΔN_{ot}) which were generated during gamma irradiation [4], [8]. The ΔN_{ot} values were obtained from the following equation [6].

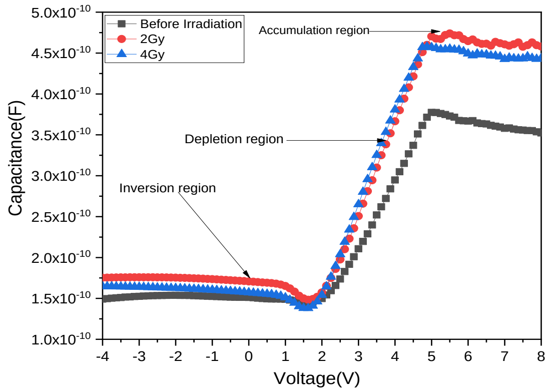

Figure 5. Capacitance-voltage(C-V) curves of Al/Yb_2O_3/SiNWs/n-Si(100) MOS capacitor.

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

where $C_{ox}=C_{acc}$ is the oxide capacitance in the accumulation region, ΔV_{mg} is the shift in the mid gap voltage, q is the electronic charge and A is the gate electrode area of the MOS device. The obtained ΔN_{ot} values for the device, which was irradiated at 0Gy, 2Gy and 4Gy are -2.18×10^{11} cm^{-2}, $-8.85\times10^{11}cm^{-2}$ and -4.33×10^{11} cm^{-2}, respectively. These values are also given in Table 1. The -2.18×10^{11} cm^{-2} can be compared to the ΔN_{ot} values reported by earlier studies. For instance, Kahraman *et al.* reported the value of ΔN_{ot}(-4.46×10-11 cm^{-2}) for Yb_2O_3 thin films and the device was irradiated at 1Gy [28]. Also, other researchers have reported ΔN_{ot} value in the range of -3.5×10^{12} cm^{-2} to -1.5×10^{12} cm^{-2} for Al_2O_3 thin films. The MOS device was exposed to 30MeV Si heavy ions at different doses of 2.23krad(Si) to 11.16krad(Si), respectively[29].

Apart from ΔN_{ot}, gamma irradiation also induced interface trapped charges(ΔN_{it}) at the high-k/ semiconductor interface. Therefore, the shift in the flat band voltage (ΔV_{fb}) was observed. Both the value of ΔV_{fb} and ΔV_{mg} were obtained from the C-V curves. These values are also tabulated in Table 1. Moreover, the ΔN_{it} can be found by using the following equation[4].

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

where ΔV_{fb} is the shift in the flat band voltage prior to and after irradiation, while other parameters have already been defined in Equation (1). The value of ΔN_{it} are found to be 2.11×10^{11} cm^{-2}, 6.37×10^{11} cm^{-2} and 6.22×10^{11} cm^{-2} at 0Gy, 2Gy and 4Gy, respectively. Also, the same values of ΔN_{it} are given in Table 1. The lowest value of ΔN_{it}($6.22\times10^{11}cm^{-2}$) was found for the device, which was exposed to 4Gy. Recently, other researchers have reported the ΔN_{it}(2.58×10^{11} cm^{-2}) at 50Gy of MOS device with Gd_2O_3 [15]. In addition, Yilmaz *et al.* also reported ΔN_{it} values 1.47×10^{10} cm^{-2} and 6.20×10^{10} cm^{-2} at 4Gy and 8Gy for HfO_2 thin films[6].

Table 1. Electrical parameters obtained C-V measurements of Al/Yb_2O_3/SiNWs/n-Si(100)/Al MOS device at different doses.

Doses (Gy)	ΔV_{mg} (V)	ΔV_{fb} (V)	ΔN_{ox} (cm^{-2})	ΔN_{it} (cm^{-2})
0	1.76	3.47	-2.18×10^{11}	2.11×10^{11}
2	0.31	4.38	-4.85×10^{11}	6.37×10^{11}
4	0.27	4.15	-4.33×10^{11}	6.22×10^{11}

In addition to ΔN_{ot} and ΔN_{it}, we also obtained the interface states density (D_{it}) by using Hill Cole-man method. So, the value of D_{it} was from the following expression[23].

$$D_{it} = \left(\frac{2}{qA}\right)\frac{G_{c,max}/\omega}{\left((G_c/\omega)/C_{ox}\right)^2+(1-C_C/C_{ox})^2} \quad (3)$$

where the $G_{c,max}/\omega$ is the corrected conductance corresponding to the maximum peak, C_c is the corrected capacitance, while other parameters have already been defined above. The calculated D_{it} at 0Gy, 2Gy and 4Gy are 6.98×10^{09} eV^{-1} cm^{-2}, 1.07×10^{10} eV^{-1} cm^{-2} and 1.14×10^{10} eV^{-1} cm^{-2}. The values of D_{it} are also plotted in Fig. 5, as a function of gamma irradiation dose. As may be noted, the D_{it} increased with an increase in the radiation dose. This attributed to the passivation of the silicon surface as the result of deposition Yb_2O_3 thin films between the metal and silicon and the reduction in number of recombination centers within the oxide layer and at the oxide/semiconductor interface [4], [15], [30].

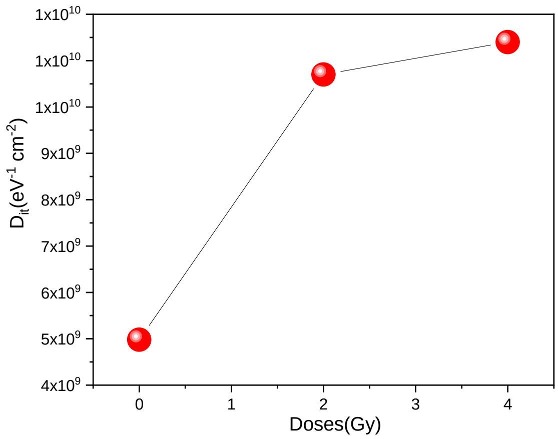

Figure 6. Interface states density depending on the gamma irradiation dose in the range of 0-4Gy.

When the device was irradiated at 2Gy the D_{it} value obtained to be 1.07×10^{10} eV^{-1} cm^{-2}. In the earlier investigations several researchers have reported D_{it} values with different high-k materials. For example, Kahraman *et al.* obtained the D_{it} value of 7.96×10^{09} eV^{-1} cm^{-2} at 0.5Gy for the MOS device with Yb_2O_3 [15]. Maurya, found the D_{it} values 3.65×10^{11} eV^{-1} cm^{-2} and 3.15×10^{11}eV^{-1}cm^{-2}at 750krad (SiO_2) and 1500krad (SiO_2) of MOS device with HfO_2 [30]. Moreover, Li *et al.* also reported the D_{it} values 1.814×10^{13} eV^{-1} cm^{-2} and 5.042×10^{13} eV^{-1} cm^{-2} at 1Mrad and 5Mrad, for HfO_2 thin films, respectively[4].

Therefore, it can be concluded that the variation in our results as compared those results reported by earlier researchers. This attributed to various experimental conditions such as doses, annealing temperature, radiation sources, annealing ambient, deposition techniques and many more.

4. Conclusion

In this study, the effect of gamma irradiation on Al/Yb_2O_3/SiNWs/n-Si (100) MOS capacitor at different doses has been investigated. We found that the capacitance value in the accumulation region decreased with an increase in the radiation dose. Also, the C-V curves shifted toward the negative voltage side as the radiation dose increased. This attributed to the generation of defects and trapped charges during gamma irradiation exposure. Finally, the D_{it} found to increase with increasing in the radiation dose. The value of D_{it} was found in the range of 6.98×10^{09} eV^{-1} cm^{-2} and 1.14×10^{10} eV^{-1} cm^{-2}.

Moreover, our future work will be investigation of gamma irradiation effect on SiNWs based sensors.

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