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RESEARCH ARTICLE

X-Ray Radiation Responses of 4H-SiC MOS with Eu_2O_3/SiO_2 Dual Dielectric

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ABSTRACT

This study examines the effects of X-ray irradiation on the structural and electrical properties of Eu_2O_3 dielectric thin films deposited on SiC substrates. The films were exposed to varying radiation durations, and their structural changes were analyzed using X-ray diffraction (XRD), while electrical properties were evaluated through capacitance-voltage (C-V) and conductance-voltage (G/ω-V) measurements. The results revealed that increased radiation exposure led to an increase in crystalline size and lattice strain, attributed to local heating and atomic rearrangements caused by radiation. Electrical analysis showed slight shifts in flat band and mid-gap voltages due to radiation-induced defects, which influenced charge trapping behavior. Despite the observed defects, the dielectric material exhibited stable electrical performance under the tested radiation conditions, indicating its potential for radiation-tolerant electronic devices. These findings highlight the applicability of Eu_2O_3 as a high-k dielectric material for advanced electronic devices operating in radiation-harsh environments.

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1. Introduction

Rare earth materials with a high dielectric constant, withstand high temperatures and radiation damage, and with an oxide thickness equivalent to SiO_2, which greatly reduces the leakage current, are excellent for replacing SiO_2 in the structure of devices based on the metal-oxide-semiconductor (MOS) structure (Bera & Maiti, 2007; Kahraman & Yilmaz, 2018; Manikanthababu et al., 2015). Radiation in general affects well or leads to the failure or deterioration of devices based on SiO_2 without a second insulator (Manikanthababu et al., 2015). Knowing that MOS structures are present in the basics of many of the electronic devices that currently exist and are based on semiconductors such as solar cells, transistors and circuits. Integrated and due to the technological importance of these devices, it is necessary to study their electrical, optical and chemical properties (Kaya et al., 2015a).

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Radiation particles can deteriorate the performance of electronic devices, and oxides are highly susceptible to radiation damage. The two main types of radiation-induced charges are the charge trapped in the oxide and the charge trapped at the Si/SiO_2 interface (Karataş et al., 2009; Kaya et al., 2015b; Yilmaz et al., 2008). The presence of the interfacial layer in the MOS device strengthens the structure of the device and is more sensitive to radiation (Kaya et al., 2015b; Wilk et al., 2001). The main components of many electronic devices are insulators and oxides, and radiation (at high doses) can lead to a significant accumulation of charges in these components and thus lead to the failure of the devices. The interface states are considered as one of the most important parameters, in addition to the role of the insulating layer formed between the oxide and the semiconductor of the manufactured structures. Therefore, the interface layer and interface states cannot be ignored, which could lead to errors in the characteristics of the MOS device, knowing that the interface layer has an important role in determining the density of interface states. It is possible to control the electrical properties by the interface states and interlayer (Karadeniz et al., 2007; Laha et al., 2011).

Radiation causes defects such as phase transformation, displacement of atoms or vacancies and voids in the MOS structure (Jiang, 2015). The field generated by the action of radiation leads to the breaking of chemical bonds and produces defects as well (Shi et al., 2019). These defects caused by radiation may affect the response MOS to radiation (Zhou et al., 2005). It has high electrons and a high breakdown electric field (Li et al., 2023). The use of a high-k material is to improve the performance of device.

Here, we present the influence of irradiation exposure time (X- radiation) on the structural and electrical properties of Eu_2O_3 films deposited on SiC substrates. To perform the purpose of this study, Al/(Eu_2O_3/SiO_2/n-SiC)/Ag MOS capacitors were fabricated via e-beam deposition method. To analyze structural properties of the irradiated and non-irradiated capacitors, XRD measurements were performed. Finally, to investigate the effect of irradiation effect on the electrical properties of capacitors, capacitance and conductance as a function of voltage at different radiation exposer time measurements were carried out. Therefore, it is important to study the effect of radiation on these materials.

2. Materials and Methods

The n-type 4H-SiC wafer was cleaned of impurities by the Radio Corporation of America (RCA) standard cleaning process to fabricate the Al/(Eu_2O_3/SiO_2/n-SiC) MOS capacitors. After the RCA cleaning process, the SiC substrate was dried with 8N purity. The dried substrate was then placed in a diffusion oven at a temperature of 900°C for growing SiO_2 layer by dry oxidation method. Pure oxygen gas was then introduced into the environment to form SiO_2 with a thickness of about 5 nm. After deposition of the interfacial transition layer, a 120 nm thick Eu_2O_3 layer was coated on the substrates using an electron beam evaporation system. They were annealed for 120 minutes at 800°C under the nitrogen atmosphere. The thin films produced after this process were divided into several parts, some without irradiation (virgin), and some of them were exposed to radiation at a fixed dose of 50 keV and a tube current of 80 µA, and the distance between the sample and the X-ray tube was 5 mm for different periods of time (2 hours, 4 hours, and 6 hours). The films were analyzed by a Rigaku X-ray diffraction (XRD) instrument with a CuKα characteristic X-ray wavelength of 1.5406 Å, and the range 2θ was between 10° and 70°. Aluminum (Al) metal (99.99% purity) was then deposited on the front surface of all the samples using a sputtering system with a 1 mm diameter circular shadow mask. The whole back side coated with silver to collect signals. Electrical measurements of C–V and G/ω–V were performed for different time periods of 300 s, 600 s, 900 s, 2100 s, 2700 s, 3100 s using a Keithley 4200-SCS parameter analyzer with a frequency of 100 kHz at room temperature. The effect of radiation exposure time on the electrical and structural properties were investigated.

3. Results and Discussion

Figure 1 shows the XRD patterns of Eu_2O_3 thin films before and after x-rays exposure to the film. The effects of x-irradiation on the crystalline structure of Eu_2O_3 films were studied by analyzing the XRD patterns. The peaks were indexed via the International Centre for Diffraction Data (ICDD) database, demonstrating a strong correlation with 65-3182 ICDD card number which is the cubic phase of Eu_2O_3 with (222) preferred orientation. It was observed that the (222) peak of intensity increased with increasing exposure time while the peak shifted to the higher angles. In a perfect crystal, when there is no internal strain associated with d-spacing, the atoms have a regular structure, and this structure is consistent with the theoretically predicted d_0 plane spacing. However, when homogeneous strain occurs in the crystal structure, the distances between atoms expand, and the distance between the reflecting planes becomes larger than d_0. In this case, the diffraction lines in the XRD pattern shift to lower angles because the larger d-spacing is associated with a lower diffraction angle. In case of non-uniform strain, the atoms in the crystal may compress at different rates. This leads to a broadening of the XRD peaks, as different regions of the crystal exhibit varying levels of strain. On the other hand, an increase in peak intensity was observed along with a shift to higher angles, that is, an increment in crystallite size. The lattice strain values were calculated to be 2.78, 2.72, 2.94 and 3.08×10^{-3} for the unirradiated, irradiated for 2h, irradiated for 4h and irradiated for 6h samples, respectively. The lattice strain values increased with the increase in exposure time as shown in Table 1. The radiation energy is able to displace the individual atoms of the material from their position by transferring kinetic energy to them. Compton scattering occurs, oxygen vacancies are formed (after breaking bonds), the formation of an interstitial defect, and the development of the granular structure, all of which affect the changes occurring in the structure of the device, and the displacement of the peaks in the XRD patterns are also related to the increase and decrease in crystallite size (Baydogan et al., 2013; Doyle, 2014; Kaleji et al., 2012; Kozlovskiy et al., 2022; Liu et al., 2021; Mazzolini et al., 2016; Subramanian & Wang, 2012; Tracy et al., 2014; Zhang et al., 2021).

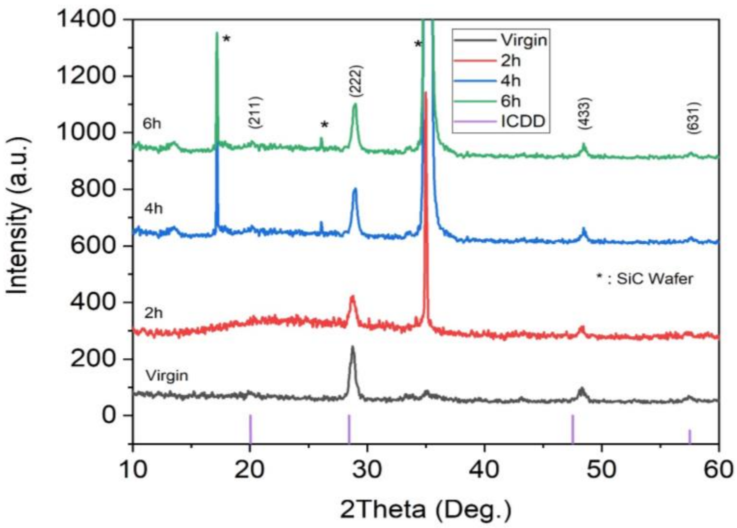

Figure 1. X-ray diffraction patterns of irradiated and unirradiated Eu_2O_3 dielectric thin films.

Table 1. Some structure parameters of Eu_2O_3 MOS at different exposure time of dose radiation.

Exposure time	**2θ (degrees)**	**Crystallite size (Å)**	**Lattice strain x 10^{-3}**
Virgin	29.376	159.62	2.778
2 hours	29.320	163.61	2.720
4 hours	29.530	205.43	2.942
6 hours	29.550	195.62	3.080

In addition, the crystallite sizes were calculated via the Scherer relationship using the (222) peak and tabulated in Table 1. The crystallite size was found to be 159.62, 163.61, 205.43 and 195.62 Å for the unirradiated, irradiated for 2h, irradiated for 4h and irradiated for 6h samples, respectively (Mozia, 2008; Mozia et al., 2009). In addition to ionization and atomic displacement that occur after radiation, radiation also causes a lattice vibration during the transfer of kinetic energy to the points of the lattice and thus leads to local heating. This heating leads to the displacement of atoms and their gathering into a larger mass. The reason for the increase in crystallite size is due to the presence of local heating of the atoms (Kaya et al., 2019; Laha et al., 2012). As a conclusion, both the crystallite size and lattice strain increased with increasing the exposure time, which is expected result.

To study the influence of radiation on the electrical properties of Eu_2O_3 films, the C-V, G-V measurements were carried out on the unirradiated and irradiated samples using an x-ray radiation source with a 50 kV energy for different exposure time periods of 300 s, 600 s, 900 s, 2100 s, 2700 s, 3100 s. The measured C-V characteristics are shown in Figure 2. Upon examining the overall C-V curve, it was observed that no abnormal degradation occurred in the structure. Ionizing radiations, such as gamma and x-rays, produce defects, interface trap- and oxide trap-charges in MOS capacitors (Ma & Dressendorfer, 1989). The interface states may act like an additional capacitance depending on whether they can follow applied voltages or not (Kaya & Yilmaz, 2015). The interface states generated by irradiation may contribute to the measured capacitance and thus, the total capacitance values increased. Capacitance changes may be a result of the voltage signal tracking these trap sites. Furthermore, when the curves were enlarged, it was observed that the flat band (V_{fb}) and midgap (V_{mg}) voltage values shifted in bi-directions due to radiation exposure. The additional exposure time periods also lead to breaking the bonds in the structure, and thus, new defects or trap centers appear and leads to confine a larger number of charges to these centers and thus lead to an increase in the flat band voltage shift (Kaya & Yilmaz, 2018). However, in some cases the broken or non-stoichiometric bonds can be neutralized by irradiation exposes (Kaya et al., 2018). Shifts towards zero volts in V_{fb} and V_{mg} indicate that positive charges are predominantly trapped within the structure (Kaya & Yilmaz, 2015, 2018; Kaya et al., 2018). Shifts towards high voltage values at certain dose levels may suggest that the trapped positive charges have been neutralized or that some trap regions created by radiation are trapping negative charges.

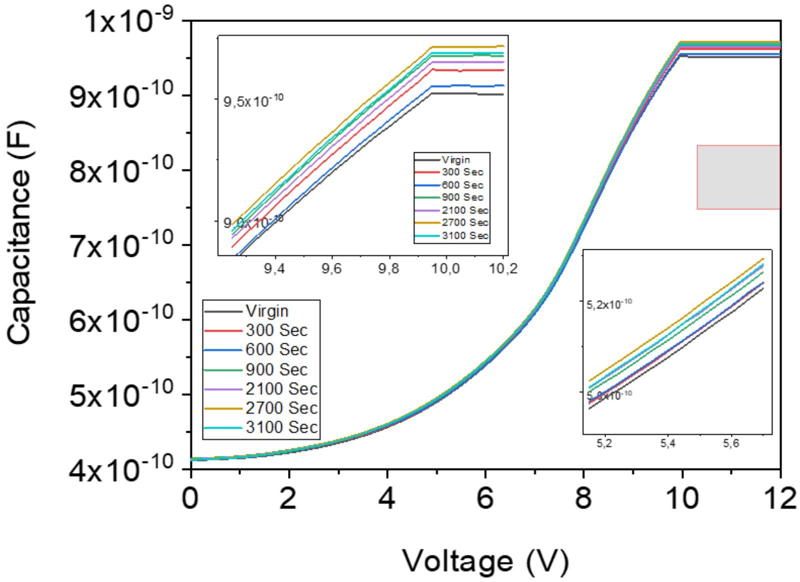

Figure 2. C-V curves showing the radiation response of a Eu_2O_3 dielectric thin film.

To determine the behavior of the interfacial states under radiation, conductivity measurements were performed, and after correcting for series resistance, the results are shown in Figure 3. As seen from this, the peak of the conductivity value increased and decreased based on the radiation dose. Since the conductivity measurement is influenced by the interaction of interface traps, it can be concluded that the trap densities change with radiation exposure. The density of interface states D_{it} was calculated using well-kwon Hill-Coleman method (Hill & Coleman, 1980). Based on the calculations, the interface trap density before and after radiation was determined to be 1.506 $x10^{12}$, 1.490 $x10^{12}$, 1.481 $x10^{12}$, 1.486 $x10^{12}$, 1.501 $x10^{12}$, 1.558 $x10^{12}$, 1.507$x10^{12}$ $(eV.cm^2)^{-1}$ for virgin, 300 sec, 600 sec, 900 sec, 2100 sec, 2700 sec, and 3100 sec exposure times, respectively. Similar to the radiation-induced oxide trapped charge density in capacitance, the interface trap densities are either neutralized or generated depending on the exposure doses. For dielectric materials to be usable in radiation detection, it is expected that one-way voltage shift behavior will emerge with increasing radiation dose. The observed behavior during the applied radiation dose suggests that the material has low dosimetric properties. However, it is important to note that this behavior may develop at higher dose ranges. The measurements indicated that the structure under investigation exhibited electrically stable characteristics under the applied radiation field. This feature highlights its potential for producing stable electronic devices in challenging radiation environments.

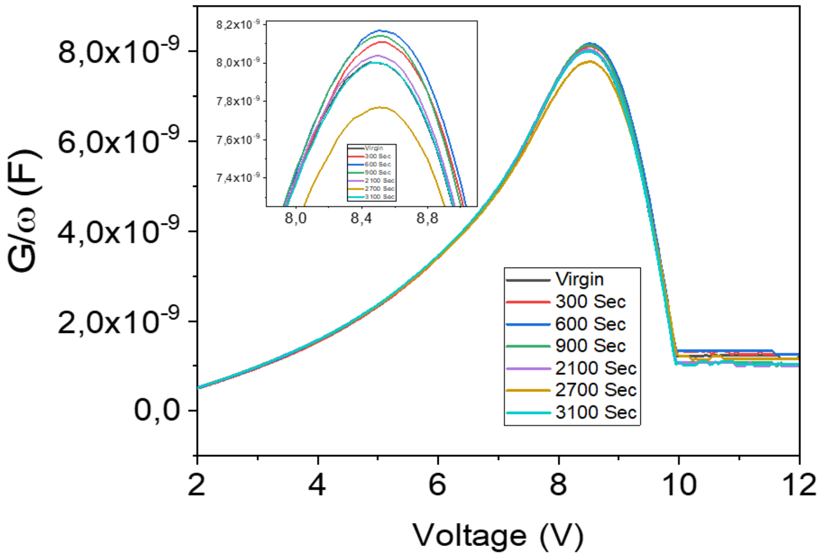

Figure 3. G/ω-V curves showing the radiation response of a Eu_2O_3 dielectric thin film.

4. Conclusion

The study investigated the effects of X-ray irradiation on the structural and electrical properties of Eu_2O_3 dielectric thin films deposited on SiC substrates. The findings demonstrated some modifications in crystallite size, lattice strain, and electrical behavior as a function of radiation exposure time. Structural analysis through X-ray diffraction revealed that increasing radiation exposure resulted in an increase in the crystallite size and lattice strain. These changes were attributed to local heating and structural rearrangements induced by radiation, confirming the impact of radiation on the structural integrity of Eu_2O_3 films. Electrical characterization via capacitance-voltage (C-V) and conductance-voltage (G/ω-V) measurements demonstrated that radiation-induced defects caused a slight alteration in the interface states and charge trapping behavior. Shifts in flat band and mid-gap voltages were observed, correlating with the formation of traps and the redistribution of charges under radiation. Despite the introduction of defects, the Eu_2O_3 dielectric exhibited stable electrical characteristics, demonstrating its resilience under the exposed radiation conditions. Furthermore, the material's response suggested limited dosimetric potential within the tested dose range. However, its structural and electrical stability under radiation highlights its viability for applications in radiation-tolerant devices. These findings underscore the importance of Eu_2O_3 as a high-k dielectric material for advanced electronic applications. Further research at higher radiation doses could provide deeper insights into its potential for radiation detection and its broader applicability in challenging environments.

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Conflict of Interest

The authors declare that they have no conflict of interest.

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