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Effects Of Gamma Irradiation On The Electrical Characteristics Of $Er_2o_3/Eu_2o_3/Sio_2$ Metal-Oxide-Semiconductor Devices For Radiation Sensor

I. G. Geidam[1], U. Y. Madaki[2] and G. Suleiman[3]
[1]Department of Physics, Faculty of Science Yobe State University, Damaturu
[2]Department of Mathematics and Statistics, Faculty of ScienceYobe State University, Damaturu
[3]Department of Chemistry, Faculty of ScienceYobe State University, Damaturu

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ABSTRACT
In this study, the effects of gamma irradiation on the electrical characteristics of $Er_2O_3/Eu_2O_3/SiO_2$ MOS deviceswere comprehensively studied and investigated.MOS devices with 15 nm thick SiO_2, 25 nm thick Eu_2O_3, and 110 nm thick Er_2O_3 stacked gate oxide layers are deposited on an n-type silicon wafer using thermal oxidation and electron beam evaporation systems, respectively. XRD and SEM measurements were obtained to analyze the structural properties of the devices. The fabricated MOS devices were irradiated in the dose range 0 – 40 Gy. The irradiation influences on the electrical properties of the devices were analyzed by studying Capacitance – Voltage measurements. Furthermore, interface state densities and oxide trap charge densities of the capacitors were calculated from the mid-gap to the flat-band put out of the measured Capacitance – Voltage (C_m – V) curves, for detailed analysis. It is observed that the flat-band shifts increase with irradiation doses, and the obtained irradiation sensitivities of the MOS devices are 110 mV/Gy for 1Gy and 26 mV/Gy for 40 Gy doses. This new structured $Er_2O_3/Eu_2O_3/SiO_2$gate dielectric oxides havethe potential to be future dielectric gate material for MOS-based radiation sensors.

Keywords: n-Si/SiO_2, Eu_2O_3, Er_2O_3, XRD, SEM, MOS devices, Gamma-irradiation, Radiation **Effects**

I. INTRODUCTION

For decades, high-k dielectrics oxides have been immensely investigated to replace SiO_2 as a gate dielectric oxides in metal-oxide-semiconductor devices (MOS devices) applications to increase the sensitivities and accurateness of the devices, due to their significant physical, electrical, and chemical properties such as thermodynamically stable with silicon, having a good electrical interface with silicon and high carrier mobility at silicon and oxides interfaces because of their large bandgap > 1 eV[1–6]. In MOS-based radiation sensors, high-k dielectric oxides are used as gate dielectrics[7–9]. Therefore, in the development of radiation sensors, the process of enhancing the gate dielectric radiation responses, which is the sensitive area of the sensors, should be considered[10–14]. Many studies have been reported on the improvement of the gate dielectric layers, however, their flat-band voltage shifts are much higher than the ideal one, which is crucial for low power electronic applications[1–4,6,15,16]. Moreover, leakage current remained an issue. Therefore, investigations on the multiple-gate dielectrics MOS devices may solve the single-layer gate dielectric's dilemma. The stacked gate dielectrics reduce the interface charge densities of the MOS devices due to the dipole polarity formations of "-/+" and "+/-" at the interfaces[1–4,6,15–17]. Furthermore, lower flat-band voltage shifts can be achieved, which is significant for the low-power device applications[2,4–6,18–20].

This study discusses the influences of gamma-irradiation on the electrical characteristics of three-layered $Er_2O_3/Eu_2O_3/SiO_2$ gate dielectrics MOS devices. To confirm the fabrication of the gate dielectric oxides, we obtained X-ray diffraction (XRD) and Scanning Electron Microscope (SEM) measurements and analyzed them. We measured capacitance-voltage measurements before and after irradiation to obtain flat-band and mid-gap voltages shifts. The authors studied the impacts of irradiation on the electrical characteristics of the MOS devices by calculating oxide trapped charge densities and interface trapped charge densities from the mid-gap to the flat-band put out of the measured capacitance-voltage curves. The authors determined and evaluated the sensitivity and electrical characteristics of the devices by analyzing the flat-band voltage shifts, mid-gap voltage shifts, oxide trapped charge density, and interface trapped charge density depending on irradiation doses.

II. EXPERIMENTAL

We deposited the $Er_2O_3/Eu_2O_3/SiO_2$ dielectric oxideson an n-type silicon wafer. Firstly, we cleaned the wafers by following the standard cleaning process of Radio Corporation of America (RCA). Secondly, we deposited 15 nm SiO_2, 25 nm Eu_2O_3, and 115 nm Er_2O_3on the cleaned wafersusing thermal oxidation and electron evaporation systems, respectively. To confirm the deposition of the desired thicknesses, we measured the thicknesses of the oxides using ellipsometry, and the desired thicknesses are confirmed. We obtained the MOS device structure by growing aluminum (Al) dots of 1.25 mm diameter on the fabricated oxides as front contact (rectifier contact) and then grown Al on the semiconductor thoroughly as back contact (ohmic contact) by the sputtering system. The obtained $Er_2O_3/Eu_2O_3/SiO_2$gate dielectrics MOS devices are illustrated in Fig. 1. We obtainedSEM and XRD measurements to investigate the structural properties of the devices.The SEM images of the thin films have confirmed the fabrication of the $Er_2O_3/Eu_2O_3/SiO_2$ dielectric oxides as given in Fig. 2. The XRD spectra of the $Er_2O_3/Eu_2O_3/SiO_2$ thin films are given in Fig. 3.

To study the responses of the MOS devices to gamma irradiation, we divided the samples into two groups and kept the first groups as a virgin with no radiation (0 Gy), we then irradiated the second groups from 1 Gy to 40 Gy under co-60 gamma irradiator. To investigate the effects of gamma irradiation on the MOS devices, we obtained Capacitance – Voltage measurements before and after irradiation at 1 MHz frequency by HIOKI 3532-50 LCR meter.From the measured capacitance, we calculated the flat-band voltage shifts, mid-gap voltage shifts, oxide trapped charge densities, and interface trapped charge densities.

III. RESULTS AND DISCUSSIONS

The gate dielectrics used between the gate electrode (metal) and the semiconductor (silicon) in the MOS-based sensors have significant impacts on the behaviors of the devices[21–27]. Therefore, new gate dielectric materials and innovative structures must be developed to improve the reliability and performance of the devices.When these devices are irradiated with radiations, such as gamma radiations and X-rays, they cause various changes in the electrical characteristics of the devices[21,24]. These ionizing radiations bring about defects, oxide charges trap, and interface charges traps and charge pairs thatcause mobile charges trapped in the MOS devices. Also, the flat-band voltage and mid-gap voltage shifts in the measured Capacitance – Voltage curves, are resulting from the variations caused by the ionizing radiations on the electrical characteristics of the MOS devices[28–31].

The measured Capacitance – Voltage (C_m – V) curves of the $Er_2O_3/Eu_2O_3/SiO_2$gate dielectrics MOS devices before (0 Gy) and after gamma irradiations (from 1 Gy to 40 Gy) are given in Fig. 4.The C_m – V curves of the MOS devices show significant responses to radiation doses, as can be seen from Fig. 4, the measured capacitance stays almost the same without a significant increment or decrement in the capacitance after irradiation. This shows that the electrical characteristics of the $Er_2O_3/Eu_2O_3/SiO_2$ MOS devices are not significantly degraded by irradiation. The flat-band and mid-gap voltages shift to the rightside (positive voltages direction) with increasing irradiation doses. It can be seen that even at 1 Gy dose a significant shift is observed, which is hardly observed in many previous studies[10–14,32]. This confirmed that $Er_2O_3/Eu_2O_3/SiO_2$ gate dielectrics are very sensitive to ionizing radiation. These variations are due to the creations of oxide trap charges and interface trap charges in the MOS devices.Furthermore, during irradiation electron-hole pairs were generated in the $Er_2O_3/Eu_2O_3/SiO_2$ gate dielectrics, and the generated charges in the gate layers were also trapped by defects as oxide trapped and interface trapped charges[7–9,21,33,34]. These trapped charges are responsible for the flat-band and mid-gap voltages shifts, and both the oxide trapped charges and interface trapped charges are effective on the $Er_2O_3/Eu_2O_3/SiO_2$ gate dielectrics layers, which is due to the new structure of the gate layers[1,2,4,19]. The right-side voltages shift behavior indicates that both holes and electrons were trapped in the $Er_2O_3/Eu_2O_3/SiO_2$ gate dielectrics MOS devices, because of the formation of dipole polarity (+/-) at the interfaces[24,33–38].

The flat-band voltages shifts (ΔV_{FB}) of the $Er_2O_3/Eu_2O_3/SiO_2$ gate dielectrics MOS devices are given in Fig. 5, the applied doses range from 1to 40 Gray.The authors depicted the error bars of the obtained flat-band voltage shifts graph to measure the variations during the measurements. The obtained variation during the measurements is found to be five percent (%5).The ΔV_{FB}shifts of the MOS devices increase with increasing applied doses, and the responses are linear.The calculated irradiation sensitivities of 155 nm $Er_2O_3/Eu_2O_3/SiO_2$ gate dielectrics MOS devices are 75 mV/Gy and 26 mV/Gy, for 0 to 4 Gy and 8 to 40 Gy irradiation doses, respectively.It can be said that the $Er_2O_3/Eu_2O_3/SiO_2$ gate dielectrics MOS device is more sensitive to gamma irradiation than many single layered-based MOS devices[10–14,32]. The responses of the devices to applied irradiation doses indicate thatthe $Er_2O_3/Eu_2O_3/SiO_2$ gate dielectrics can be used in MOS-based devices radiation sensors as the gate dielectric layer.

The authors investigated the impacts of gamma irradiation on the oxide traps charge density by calculating the changes of the oxide trapped charge densities(ΔN_{ot}) from the mid-gap voltages shifts (ΔV_{mg}) using the following equation:

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

Where C_{ox}, ΔV_{mg}, q, and A, are oxide capacitance of the MOS devices, mid-gap voltages shifts, electric charge (1.602 $\times 10^{-9}$C), and area of the MOS devices, respectively. The variations of the oxide trapped charges with the applied irradiation doses are given in Fig. 6. The oxide trapped charges are the main cause of the ΔV_{FB}shifts. As seen in Fig. 6, the calculated ΔN_{ot}values are negative, which indicates that electrons are trapped in the $Er_2O_3/Eu_2O_3/SiO_2$gate dielectrics. The obtained ΔN_{ot}increase with increasing applied irradiation doses from 1 to 40 Gy linearly.

Although the impacts of oxide trapped charges on theΔV_{FB} shifts are more significant than the interface trapped charges, this study shows that the interface trapped charges make a significant impact on the Capacitance – Voltage shifts. The authors calculated the interface trapped charge densities (ΔN_{it}) of the MOS devices using the following equation:

$$\Delta N_{it} = -\frac{C_{ox}\,(\Delta V_{FB} - \Delta V_{mg})}{qA} \qquad (2)$$

Where $C_{ox}$is the oxide capacitance, ΔV_{FB} is the flat-band voltage shift,$\Delta V_{mg}$is the mid-gap voltage shift,q is the electric charge, and Ais the area of the MOS devices. The variations of $\Delta N_{it}$with the applied irradiation doses are given in Fig. 7. The obtained ΔN_{it} is complex, it increases from 1 to 4 Gy and then decreases from 4 to 8 Gy, again increases to 16 Gy, finally decreases to 40 Gy. This behavior indicates that due to the structure of gate dielectrics of the MOS devices surface band bending has occurred, which causes the impact of the $\Delta N_{it}$to be significant. The dipoles formation of (-/+) and (+/-) polarities at the $Er_2O_3/Eu_2O_3/SiO_2$interfaces brought about donor-like and acceptor-like interface traps in the $Er_2O_3/Eu_2O_3/SiO_2$ gate dielectrics MOS devices.

IV. CONCLUSIONS

The effects of gamma irradiation on the electrical characteristics of $Er_2O_3/Eu_2O_3/SiO_2$ MOS devices were comprehensively studied and investigated. The behaviors of the MOS devices under Co-60 gamma irradiation show that radiation has influenced the Capacitance – Voltage characteristics of the devices. Both the flat-band voltage and mid-gap voltage shifts increase with the increasing applied irradiation doses. The calculated sensitivities of the $Er_2O_3/Eu_2O_3/SiO_2$gate dielectrics are much higher than many single-layered gate dielectrics, which are 75 mV/Gy and 26 mV/Gy. It is observed that electrons are trapped in the $Er_2O_3/Eu_2O_3/SiO_2$ gate dielectrics, which is due to the variation in the interfaces and generation of oxygen vacancies. We also observed that charges trapped in the oxide are more than the charges trapped in the interface. Therefore, the impacts of oxide trapped charges to the flat-band and mid-gap voltages shifts are more effective than the interface trapped charges. These outcomes suggest that $Er_2O_3/Eu_2O_3/SiO_2$ gate dielectrics can be the future gate dielectric in radiation sensors applications.

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