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Frequency dependent gamma-ray irradiation response of Sm_2O_3 MOS capacitors

S. Kaya [a,*], E. Yilmaz [a,b], A. Kahraman [a,c], H. Karacali [a,b]

[a] Nuclear Radiation Detectors Research and Development Center, AIBU, 14280 Bolu, Turkey
[b] Physics Department, Abant Izzet Baysal University, 14280 Bolu, Turkey
[c] Physics Department, Uludag University, 16059 Bursa, Turkey

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ABSTRACT

The frequency dependent irradiation influences on Sm_2O_3 MOS capacitors have been investigated and possible use of Sm_2O_3 in MOS-based radiation sensor was discussed in this study. To examine their gamma irradiation response over a range of doses, the fabricated MOS capacitors were irradiated up to 30 grays. Capacitance–Voltage (*C–V*) measurements were recorded for various doses and the influences of irradiation were determined from the mid-gap and flat-band voltage shifts. In addition, the degradations of irradiation have been studied by impedance based leakage current–voltage (*J–V*) characteristics. The results demonstrate that *J–V* characteristics have not been significantly change by irradiation and implying that the excited traps have a minor effect on current for given dose ranges. However, the frequency of applied voltage during the *C–V* measurements affects the irradiation response of devices, significantly. The variations on the electrical characteristics may be attributed to the different time dependency of acceptor and donor-like interface states. In spite of the variations on the device characteristics, low frequency measurements indicate that Sm_2O_3 is a potential candidate to be used as a dielectric layer in MOS based irradiation sensors.

1. Introduction

The bare metal–oxide–semiconductor (MOS) capacitors are the base of the MOS-based device, e.g., MOSFETs and ICs. Therefore, understanding of the device characteristics of MOS capacitors is important for development of novel MOSFET technology [1]. The studies related to design and characterization of the MOS devices have been performed to its better performance for various filed since the last few decades [2–5].

MOS devices used for irradiation measurements have attracted special attention recently and have been widely used in most dosimeters for monitoring radiation doses in various environments such as space, nuclear industry, and medical applications. This is mainly due to their linear performance over the intended energy range and superior sensitivity. The existence of an oxide (dielectric) layer in MOS structures makes MOS-based devices more sensitive to irradiation environments. Majority of the radiation-induced damages are located at oxide bulk and/or near the oxide–semiconductor interface. Additionally, the exposure of these structures to high-level particles results in a considerable amount of lattice defects. The generated defects that act as recombination centers or minority/majority carrier trapping centers cause degradation of these device performance and their applications. Therefore, influences of radiation on the electrical characteristics of MOS devices are complicated in nature [5]. Various dielectric materials such as Al_2O_3 [6], HfO_2 [7,8], TiO_2 [9,10], La_2O_3 [11] and ZrO_2 [12] have been studied for MOS-based technology to substitute conventional SiO_2 layer. However, there is not enough knowledge in the literature about their radiation responses. The investigations of finding new alternative dielectric materials are crucial for development of MOS-based devices to be used in irradiation environment. Thus, samarium oxide (Sm_2O_3) could be one of the suitable dielectrics compared to other dielectric materials due to the fact that it maintains many attractive features in itself alone such as high dielectric constant up to 30 [13,14] depending on film quality, thermodynamically stable on the underlying Si surface up to 1000 °C preventing the formation of silicide layers and rough surfaces [15], wide band gap [16], and large conduction band offsets [17].

In order to investigate influences of irradiation on the electrical characteristics of Sm_2O_3 MOS capacitors, the samples were irradiated by using the Co-60 gamma ray source from 0.6 to 30 grays.

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* Corresponding author. Tel.: +90 374 254 10 00/8752.
E-mail address: senolkaya52@gmail.com (S. Kaya).

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The electrical characteristics of the device were investigated from capacitance–voltage (*C–V*) and impedance based leakage current density–voltage (*J–V*) measurements at high (1 MHz) and low (100 kHz) frequencies. It is known that frequency dependent charges have crucial effects on the electrical characteristics of MOS capacitors [18–20] and very few studies exist in the literature for irradiation dispersion on various frequencies. The forgoing two different frequencies have been selected to study influence of frequency dependent interface state to radiation response of device characteristics. The influences of irradiation were determined from the mid-gap and flat-band voltage shifts of capacitance curves and radiation induced impedance based leakage current characteristics.

2. Experimental details

The Sm_2O_3 thin films were deposited on n-type (100) Si substrate with a resistivity of 1–4 ohm cm by reactive RF sputtering from a 4-inch Samarium target with purity of 99.99%. Before the deposition of Sm_2O_3 layers, the wafers were cleaned with standard RCA cleaning process. Prior to commencing sputtering, the base pressure of the chamber was below 4.0×10^{-4} Pa and sputtering gas pressure was at 1.0 Pa. The pre-sputtering was done for 10 min at 200 W to remove any impurities present on the target surface. During the commencing sputtering process, the n-Si substrates were being heated at 200 °C and sputtering power was adjusted to be 200 W. The reactive gas mixture of ultra-pure Ar (99.9999%) and O_2 (99.9999%) was used in sputtering process. The films were grown in one of the ideal argon-to-oxygen flow ratio (Ar/O_2) 15/10 sccm as in the literature [21]. Then, the deposited films were annealed at 800 °C for 40 min under Nitrogen environment. The detailed structural characterizations were performed in our previous study [22] and the fabricated thin films are found to be monoclinic B-type crystal structure with smooth surface. The thicknesses of the deposited films were measured to be 120 nm by ellipsometry. The back ohmic contacts were made-up of aluminum (Al) which was deposited by sputtering on the back side of wafers for annealed samples. The MOS front Al electrodes were formed in circular dots with 2.2 mm diameter by Al deposition through a shadow mask at base pressure of 1.3×10^{-3} Pa.

In order to study response of MOS capacitor to gamma irradiation, MOS devices were irradiated using a Co-60 gamma source from 0.6 to 30 grays at a dose rate of 0.0068 Gy/s. *C–V* measurements were performed prior to and after irradiation at high (1 MHz) and low (100 kHz) frequencies. The degradation levels of devices were also investigated at high and low frequencies by impedance based leakage current density–voltage (*J–V*) characteristics. In order to obtain leakage current density, the total impedance of devices were measured by using HIOKI 3532-50 LCR meter at high and low frequencies, and then leakage current densities were calculated by well-known Ohms' law.

3. Results and discussions

The capacitance characteristics of fabricated MOS devices provide a very delicate tool to study irradiation effects on the dielectric layer and their interfaces between dielectric and substrate [23]. However, before the study of irradiation response of devices, frequency dispersion of non-irradiated capacitances curves had been investigated. The obtained capacitance curves for low and high frequencies are illustrated in Fig. 1. The measured capacitance increase and flat-band voltage shifts toward more negative values with decreasing frequency for non-irradiated capacitance curves as shown in Fig. 1. Several parameters e.g., series resistance and frequency dependent charges, are responsible for the variations on the capacitance, but the frequency dependent interface states are primary reason of the changes on the capacitance values [18,23,24]. At low frequencies interface states act like a yield capacitance, hence this yield capacitance contributes to the measured capacitance characteristics. However, at higher frequencies, since the interface states do not have enough time to follow the applied voltage signal, the contribution of interface states to the measured capacitance is almost zero [25–27].

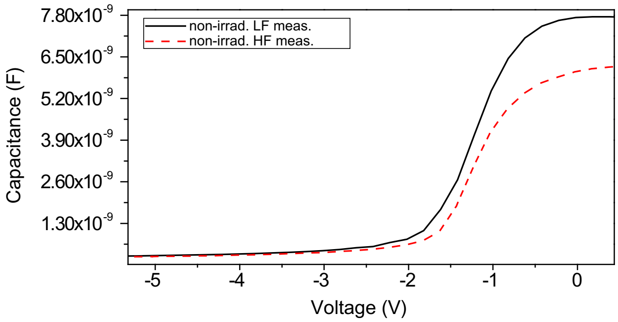

Fig. 1. The measured capacitance characteristics at low (100 kHz) and high (1 MHz) frequencies.

The dielectric characteristics might show variation depending on the film quality and were calculated by HF capacitance measurement using the well-known capacitance formula ($C_{ox} = \varepsilon\varepsilon_0 A/d$), to eliminate the time dependent impurity effects. The measured capacitance value of the Sm_2O_3 MOS capacitor is 6.18×10^{-9} F in the strong accumulation region, and the dielectric constant (k) was calculated and found to be about 22 which is lower than epitaxial Sm_2O_3 layer [13], but significantly higher than other reported values [14,28,29]. Moreover, variations on the flatband voltages have been also observed with applied voltage frequency. The sign of the frequency-dependent charges is responsible for the direction of voltage shifts on the flat-band. At lower frequency, the flat-band voltages shift toward more negative values, which indicate that the majority of the trapped time dependent charges at interface states are holes in the structure. This initial interface state density occurred during the fabrication process. The initial densities of interface states have been calculated by using HF–LF capacitance method [18], and found on order of 10^{12} cm^{-2} from our previous study [30]. The obtained order is higher than conventional SiO_2 layer. However, it is in the same order as other promising dielectrics reported in the literature [6,7,31,32].

The capacitance characteristics as a function of gate voltage at low (100 kHz) and (1 MHz) high frequencies for various gamma-ray irradiations of Sm_2O_3 MOS capacitors are depicted in Fig. 2(a and b). MOS capacitors exhibit different irradiation responses for high and low frequencies. Ionizing radiations, such as gamma rays and X-rays, generate defects, interface trap- and oxide trap-charges in MOS structure [33]. Hence, ionizing radiation may cause variations in the capacitance, shifts in flat band and midgap voltages. The measured capacitance values slightly increase after first 0.6 gray irradiation exposures and almost ramain the same after further doses for LF measurements. The basic modification on the low frequency *C–V* curves is shift on the flat band and midgap voltages towards positive voltages. On the other hand, capacitance measured at high frequency, was significantly enhanced with irradiation doses. In addition, flat band voltages are slightly shifted toward negative voltages.

Two possible mechanisms might be reasons of the variation on the measured capacitance values at high frequency: (i) the contribution of generated interface states capacitance to measured capacitance [23] and (ii) passivation of the defect densities in the