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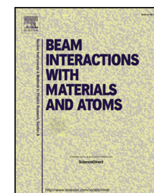

FET-based radiation sensors with Er_2O_3 gate dielectric

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ABSTRACT

Pre-irradiation device characteristics, gamma radiation response, and possible use in radiation dosimetry have been investigated for MOSFETs with a 100 nm thick Er_2O_3 gate dielectric. The performance of these novel devices has been compared with that of commercial pMOS dosimeters (RadFETs) with a standard SiO_2 gate oxide of the same thickness. The radiation sensitivity of the Er_2O_3 is significantly higher than that of SiO_2, and this is particularly pronounced at lower dose levels. Significantly larger numbers of positive charges are trapped in the Er_2O_3 dielectric than in SiO_2 during irradiation exposure, resulting in increased threshold voltage shift. After two weeks of room temperature annealing, 11.9% and 24.0% fading have been observed in SiO_2 and Er_2O_3 samples, respectively. Higher fading for Er_2O_3 may be related to higher number of shallow traps close to the dielectric/silicon interface. These initial results are promising for the possible use of Er_2O_3 as a new gate dielectric in pMOS dosimeters. The observed enhancement of device sensitivity can be a milestone for the introduction of the pMOS dosimeters in personal dosimetry applications.

1. Introduction

The use of Metal-Oxide-Semiconductor Field-Effect Transistor (MOSFET) as a radiation dosimeter was first reported by Holmes-Siedle [1]; this device is known as RadFET, MOSFET dosimeter, or pMOS dosimeter. The RadFETs have been used in various applications, such as space-radiation dose measurements [2], heavy ion experiments [3], and clinical radiotherapy [4–6]. Instant and non-destructive readout, low power consumption, compatibility with microprocessors, and easy calibration procedures are the main good features that have led to the popularity of these devices [4,7,8].

The operation principle of the RadFETs is based on the radiation induced threshold voltage shift due to charges trapped in the gate oxide, which is a function of absorbed dose [9]. The gate dielectric, which has been a conventional Silicon Dioxide (SiO_2) layer since device discovery, is the sensitive region for the commercial RadFETs [4,6,7,10]. Researchers have been spending a great effort to enhance the sensitivity of these devices, especially for use as personal dosimeters [7,8,11–14]. The studies have focused on improvement of sensitivity of the standard SiO_2 dielectric by various methods: increase of the dielectric thickness, boron implantation, stacked approaches, etc. However, our previous basic research studies on simple laboratory grown MOS capacitor structures have demonstrated that the use of high-k dielectric materials, such as Aluminum Oxide (Al_2O_3) [15], Samarium Oxide (Sm_2O_3) [16], and Erbium Oxide (Er_2O_3) [17] can increase radiation sensitivity of the oxide- layer. The SiO_2 is more cost effective and technology compatible layer than potential high- k materials. The minimal detectable dose for single SiO_2 based NürFETs is around the few mGy. This sensitivity is useful for the space and high energy physics applications where high irradiation field exist. However, requirement radiation sensitivity of dosimeters should be improved for the medical applications and must reach to few µGy for devices to be used in personal dosimetry for workers [18]. Hence, different materials should be investigated in order to enhance radiation sensitivity of the FET based detectors. The previous reported MOS studies mentioned above with high- k materials were in form of laboratory grown simple capacitor structures. The responses of fully processed MOS transistors with high-k gate stacks under realistic semiconductor processing conditions have not been studied so far. Hence, among previously investigated high-k materials, Er_2O_3 has been selected as one of the most promising materials, with low initial interface trap density, thermal stability with Si, and high offset values [17,19–24]. The Er_2O_3 pMOS transistors were fabricated in the Abant Izzet Baysal University Nuclear Radiation Detectors Research and Applications Center (NÜRDAM), Bolu, Turkey; and we call these devices NürFETs. In the present, study the pre-irradiation characteristics and radiation response of Er_2O_3 NürFETs has been investigated with the view of a possible use in radiation dosimetry. The performance of Er_2O_3 NürFETs has been compared with that

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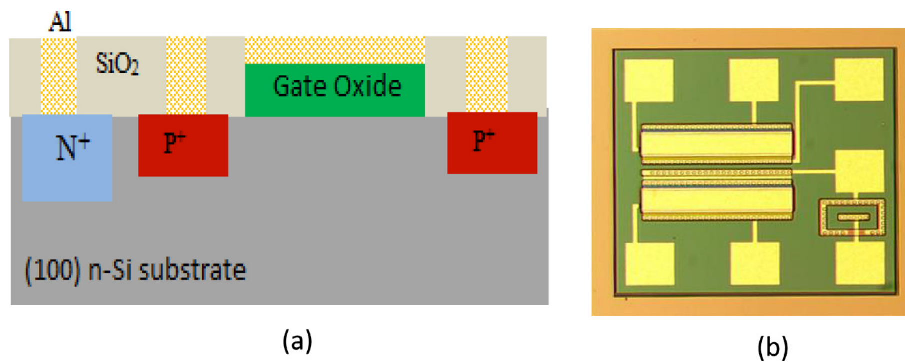


Fig. 1. Fabricated NürFETs (a) schematic cross section, and (b) images under metallurgical microscope.

of standard commercial SiO_2 RadFETs fabricated in Tyndall National Institute, Ireland.

2. Experimental details

2.1. Device fabrication

The Nuclear Radiation Sensing Field Effect Transistors (NürFETs) with the Er_2O_3 gate dielectric were fabricated by Abant Izzet Baysal University Nuclear Radiation Detectors Research and Applications Center, Bolu, Turkey. The schematic structure and images under the metallurgical microscope of fabricated devices are depicted in Fig. 1(a) and (b), respectively. Each chip contains two individual NürFETs with a channel width of W = 300 µm and a channel length of L = 50 µm. One of NürFET has a common substrate pin, while the other terminals are independent. The other NürFET source and bulk terminals are internally connected, while drain and gate terminals are independent. During the fabrication process, six-inch (1 0 0) n-type Si wafers with the resistivity of 1–4 Ohm-cm were used as starting material. Following the Radio Corporation of America (RCA) cleaning process, a field oxide layer of approx. 1 µm was grown by wet oxidation at 1100 °C. The photolithography and wet-chemical etching were carried out to define doped areas. The n^+-doped regions were formed by phosphorus diffusion (using $POCl_3$), and p^+-regions were formed by boron diffusion (using BBr_3). Another lithography, wet etching and RCA cleaning process were performed respectively to form channels where Er_2O_3 gate dielectric layer was deposited. Following the gate channel formation, the Er_2O_3 gate dielectric layer was deposited by RF sputtering. During the sputtering process a 99.99% pure four-inch Er_2O_3 target was used and the sputtering power was adjusted to 300 W with 16 sccm ultra-pure Ar flow. To study structural and morphological characteristics of the gate dielectric, the Er_2O_3 layers were also deposited on separate similar Si wafers following the same procedure. After the deposition, the devices and deposited films were annealed at 350 °C in nitrogen for 30 min. The thicknesses of the dielectric layers were measured to be 100 nm using spectroscopic reflectometer. Crystallographic structure and gate dielectric morphology were investigated by X-ray diffractometry (XRD) and Atomic Force microscopy (AFM), respectively. Aluminum was used for metallization procedure and then the post-metallization anneal was performed at 150 °C for 30 min in the presence of Nitrogen to complete Er_2O_3 NürFET fabrication. In order to compare device specifications and to discuss possible use of Er_2O_3 NürFETs as radiation dosimeters, commercial p-channel RadFETs with 100 nm SiO_2 gate dielectric, fabricated by Tyndall National Institute – Ireland, were also used in this study.

2.2. Electrical characterizations and irradiation test

Transfer characteristics ($I_d - V_{gs}$) and charge pumping curves were measured to determine initial (pre-irradiation) device characteristics. Using the initial device characteristics including the interface trap density and threshold voltage, usability of Er_2O_3 NürFETs in microelectronic applications has been discussed. During the irradiation experiment four Er_2O_3 and four Tyndall pMOS samples were used. The samples were exposed to several Co-60 gamma irradiation doses up to 1600 Gy with a certificated Ob-Servo Sanguis Co-60 gamma irradiator with approximate dose rate of 417 Gy/h in the Turkish Atomic Energy Authority Gamma Irradiation Facility. The devices were irradiated with zero gate bias (all terminals grounded) during irradiation. Threshold voltage (V_{th}) values were determined by using constant- current methods [25], i.e., V_{th} values were determined as voltage values at the specified current level (10 µA for SiO_2 RadFETs, and 1 µA for Er_2O_3 NürFETs). In addition, transfer characteristics (I_d-V_{gs}) were measured before irradiation and after each dose step. The McWhorter and Winokur's [26] midgap sub-threshold charge separation technique was used to calculate radiation-induced trap densities. The threshold voltage recovery (fading) characteristics of the devices during room temperature annealing were also investigated.

3. Results and discussion

3.1. Pre-Irradiation characterization

The crystallographic and morphological parameters of dielectric layers directly influence electrical properties of devices [27–29]. Therefore, the analysis of these parameters should be considered to enhance reliability of the study. The XRD and AFM measurements are given in Fig. 2(a) and (b) for Er_2O_3/Si films to observe the annealing effects. The peaks were indexed by International Centre for Diffraction Data (ICDD) base and the indexed peaks are in agreement with the peaks of the Er_2O_3 cubic phase with card no: 77-0463 [17]. It was observed the films were highly oriented in (2 2 2) and (4 4 4) orientations and minor peaks intensities were vaguely seen in enlargement of the XRD scans. Presence of strain and stress on the films may influence the crystalline orientation of the deposited layer [30]. Hence, possible stress and strains on the film may influence crystallographic orientation of the Er_2O_3 layer. In addition, the grain size of the films was calculated from boarding of intense peak (2 2 2) using Scherrer's equation [17,31] to be 22.15 nm. On the other hand, the AFM measurement is depicted in Fig. 2(b). The surface roughness (R_q) was calculated to be 2.8 nm. The calculated R_q is relatively low compared to the Er_2O_3 thin films deposited by PVD methods [32,33], indicating uniform surface morphology has been obtained.

The initial electrical device parameters for assessment of Er_2O_3 NürFETs use in microelectronics have been analyzed and the obtained results were compared to Tyndall RadFETs having the same thickness of SiO_2 gate dielectric. To do this, the I_d-V_{gs} transfer characteristics and charge pumping measurements were performed; results are given in Fig. 3(a) and (b), respectively. As expected, no anomalous kinks were observed in the transfer curves, although the large shift toward more

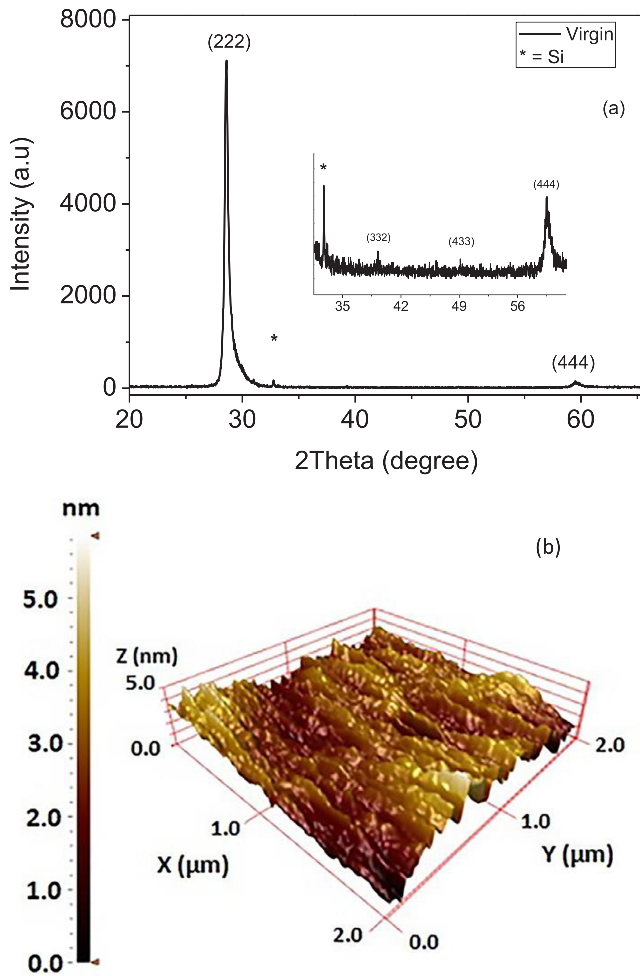
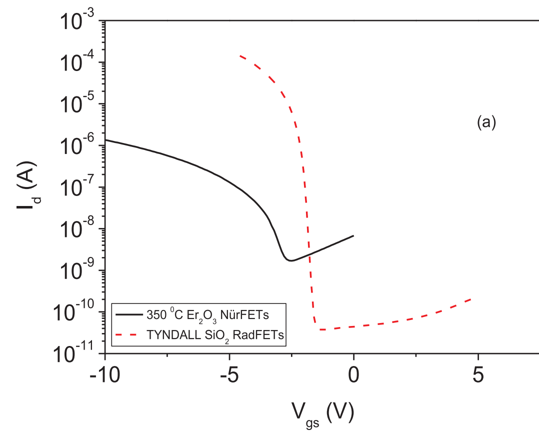


Fig. 2. The a-) XRD of deposited and annealed films, b-) AFM measurements of the annealed Er_2O_3/Si thin films.



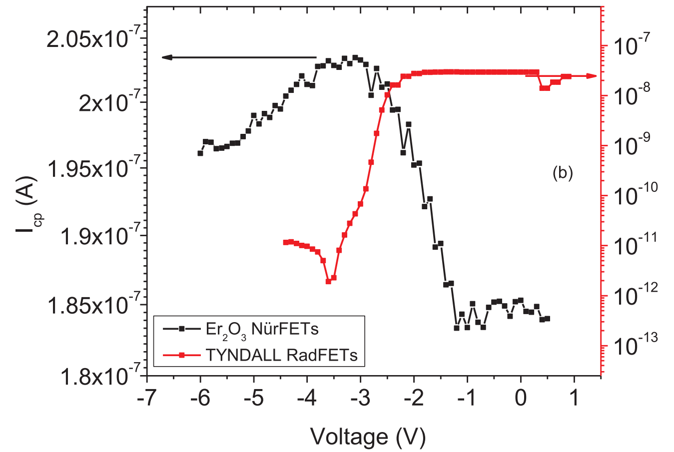


Fig. 3. The (a) transfer $I_d - V_{gs}$ characteristics and (b) Charge pumping current measurements of the Er_2O_3 NürFETs and Tyndall RadFETs.

negative values and higher leakage current has been observed at low voltages compared to SiO_2 RadFETs. The reason for higher transfer current at low voltages is associated with leakage effect [34,35] and the lower slope of the curve is due to trapped charges in the device structure during the fabrication process [36]. The V_{th} values for unirradiated devices are given in Table 1. Owing to trapped positive charges during the fabrication and lower dielectric capacitance of Er_2O_3 than expected, initial threshold voltages of Er_2O_3 NürFETs are higher than that of conventional SiO_2 RadFETs. Alternative deposition methods, such as Atomic Layer Deposition (ALD), should be used in further studies in order to improve oxide quality and reduce the initial V_{th} values [37,38].

In addition, the initial interface trap (D_{it}) were calculated from Eq. (1) [9], using the peak values in charge pumping curves in Fig. 3(b).

$$D_{it} = \frac{I_{cp,max}}{fqA} \quad (1)$$

where A = L × W is the area under the gate (in our case L = 300 µm, W = 50 µm), f is the voltage pulse frequency and q is the electron charge. The D_{it} values for the Er_2O_3/Si interface are also given in Table 1. This value is close the conversional SiO_2/Si interface trap density and such low D_{it} values for Er_2O_3/Si interface have been also reported in previous studies [17,39]. Considering the pre-irradiation device analysis, despite the higher trapped charge density in the dielectric layer, it was observed that the fabricated Er_2O_3 NürFETs were suitable for further investigation.

Table 1
The V_{th} and D_{it} parameters of studied devices before irradiation.

	V_{th} (V)	D_{it} ($\times 10^{10}$ cm^{-2})
Er_2O_3 NürFET	−9.00	8.51
SiO_2 RadFET	−2.61	1.05

3.2. Irradiation response of devices

The effect of irradiation on electrical I_d-V_{gs} characteristics of SiO_2 RadFETs and Er_2O_3 NürFETs are illustrated in Fig. 4(a) and (b), respectively. Threshold voltage shift with the radiation dose is given in Fig. 4(c) for both types of samples. The $I_d - V_{gs}$ characteristics of the both devices shift toward more negative voltages. The accumulation of the positive trapped charge densities in the main reason of these observed V_{th} shifts [40] which is discussed in details below. Basic mechanism of the irradiation induced effects for SiO_2 gate dielectric is well-known [41,42]. Briefly, the irradiation generates number of new defects and electron-hole (e-h) pairs. Owing to higher mobility of electron, they are easily swept out from the gate, while holes which escape initial recombination move toward SiO_2/Si interface where deep traps are located. The radiation-induced defects and the trapped holes cause the shifts in threshold voltages as seen in Fig. 4(a). Similar negative voltage shift in the Er_2O_3 NürFETs under irradiation exposure indicates that the holes are trapped in the device structure [8,9,17,42]. Generation of oxygen vacancies under radiation exposure have been confirmed by our previous Er_2O_3 thin film study [43]. The oxygen vacancies have been known as hole trap centers [44,45]. Hence, the continuous negative threshold voltage shift for Er_2O_3 NürFETs can be

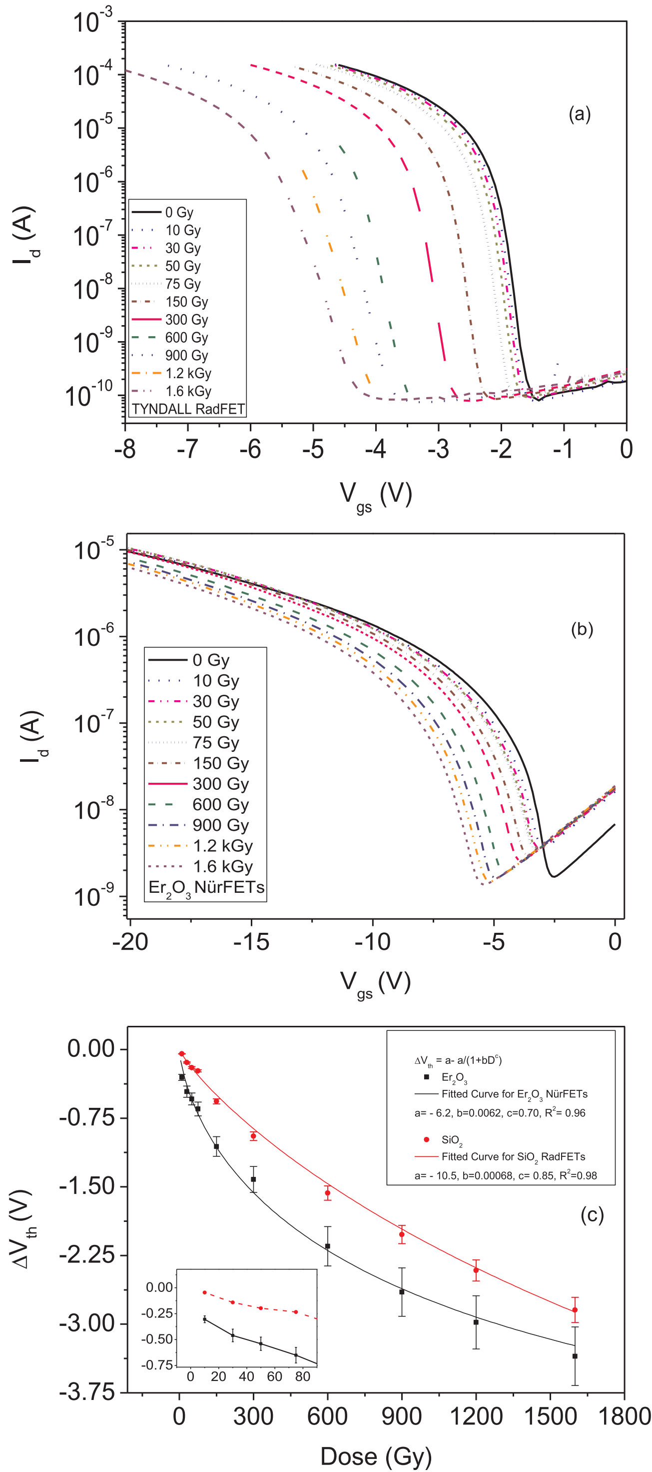


Fig. 4. The $I_d - V_{gs}$ transfer characteristics of (a) Tyndall RadFETs, (b) Er_2O_3 NurFETs during irradiation, and c-) Threshold voltage shift dose relations for the devices.

attributed to generation of oxygen vacancies under irradiation.

The fitted curves describing shifts in the threshold voltage (ΔV_{th}) – dose relationship are shown in Fig. 4(c). Similar trend was observed for both samples. Relatively large standard deviations shown in error bars for Er_2O_3 NürFETs are probably associated with device-to-device in process variations during the Er_2O_3 deposition by sputtering [46]. The radiation- induced shift in V_{th} (in Fig. 4(c)) can be expressed by a fitted non-linear Equation [9]:

$$\Delta V_{th} = a - \frac{a}{1 + bD^c} \tag{2}$$

The values of the fitting coefficients, a, b, and c, are shown in the inset in Fig. 4(c). The linearity of the ΔV_{th} – dose relationship of the devices decreases at higher doses. The accumulation of positive radiation-induced oxide trapped charge leads to electric field screening at higher doses, causing the sub-linear behavior of the sensor [4,5]. The radiation sensitivity ($S = \Delta V_{th}/D$) of the Er_2O_3 is higher than that of SiO_2, and this is particularly pronounced at lower dose levels. For example, sensitivity of Er_2O_3 NürFETs at 30 Gy is 15 mV/Gy vs. only 4.6 mV/Gy for SiO_2 RadFETs. However, the SiO_2 RadFET's response is more linear with those than Er_2O_3 NürFET's comparing the goodness of fitness values (R^2) [4]. Thus the difference in sensitivities decreases with dose – 7.2 mV/Gy (Er_2O_3) vs. 3.8 mV/Gy (SiO_2) at 150 Gy, and 2.1 mV/Gy (Er_2O_3) vs. 1.88 mV/Gy (SiO_2) at 1600 Gy. The data confirms previous findings of significant voltage shifts in irradiated Er_2O_3 capacitor structures [17]. It should be noted that, to the best of our knowledge, these are the first data that show comparable sensitivities of full transistor structures with high-k dielectrics to those with standard SiO_2. Further investigation will be needed to optimize Er_2O_3 dielectric and reinforce the findings of this initial study; nevertheless it can be concluded that the Er_2O_3 shows excellent promise to replace SiO_2 for MOSFET dosimetry applications.

The radiation sensitivity of the dielectrics depends on several factors, such as the effective atomic number (Z_{eff}) of the gate dielectric, film quality, trapping efficiency, etc. Higher Z_{eff} number increases the probability of the radiation interaction with the material. Hence, larger initial hole yield and larger number of defects, where holes are trapped, can be generated. Higher sensitivity of the Er_2O_3 dielectrics is possibly associated with higher Z_{eff} value of Er_2O_3 than SiO_2. It should be noted that Z_{eff} is not only the factor to enhance radiation sensitivity of devices. Some dielectrics, like HfO_2, have also higher Z_{eff} number than SiO_2 but they exhibit lower radiation sensitivity due to charge trapping distribution/efficiency [47]. Trapped charge distribution in high- k gate dielectrics are somewhat more complex to what has been observed in thermal SiO_2 and each dielectric responses should be considered separately [16,48,49].

The irradiation induced oxide trapped charge (ΔN_{ot}) and interface trapped (ΔN_{it}) charge densities during irradiation are shown in Fig. 5(a) and (b), respectively. The ΔN_{ot} and ΔN_{it} increase with dose for both Er_2O_3 and SiO_2 devices. The sign of trapped charges is positive for both interface traps and oxide trapped charge. However, for some alternative high-k gate dielectrics and its interface underlying the semiconductor layer, such as HfO_2/Si [46], Sm_2O_3/Si [16], exhibits both electron/hole trapping and passivation of trapped charges under radiation exposure [47,50]. These bi-directional trap formation and passivation of trapped charges reduce the radiation sensitivity of devices. In these Er_2O_3 samples, the trapping of holes at the trap centers (basically oxygen vacancies in Er_2O_3 [43]) dominates over electron trapping. The continuous generation of holes traps during irradiation significantly contributes to the radiation sensitivity of the Er_2O_3 dielectric layer.

Comparing the ΔN_{ot} and ΔN_{it} values in Fig. 5, it can be seen that in both type of samples, and particularly in Er_2O_3, more trapping occurs in the dielectric than at the dielectric/substrate interface. This confirms that the oxide trapped charges are responsible for the V_{th} shift. Further, the number of both types of radiation- induced oxide and interface trapped charge is significantly higher in Er_2O_3 samples. This is correlated with higher density and Z_{eff} number of Er_2O_3, which enhance the radiation absorption probability. The Monte Carlo simulations have also confirmed the energy deposition in the dielectric and electron-hole generation are significantly enhanced in high-k dielectrics [51,52].

Besides the sensitivity, a long term stability of ΔV_{th} after irradiation is also important parameter for pMOS dosimeters. The fading characteristics have been assessed during room temperature post-irradiation annealing with zero gate bias and results are shown in Fig. 6. The

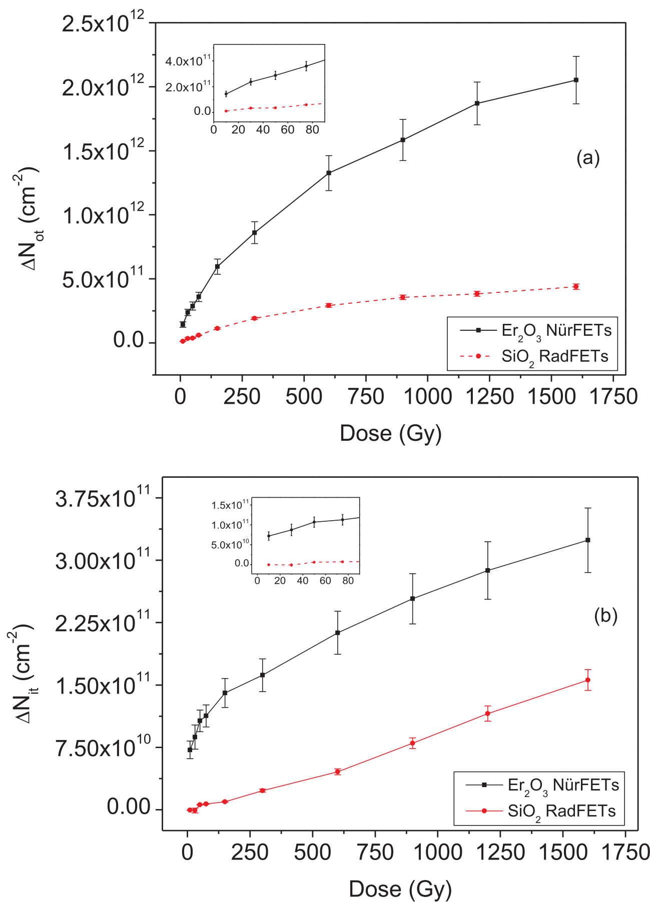


Fig. 5. Radiation induced (a) oxide trap density, and (b) interface trap density at various doses.

11.9% percentage fading after two weeks for the SiO_2 RadFETs is in agreement with the literature [10,53]. The Er_2O_3 sample fading is significantly larger, exceeding 20%, which indicates the need for further optimization of this technology. The fading is mainly associated with the recombination of the trapped charge located in the shallow trap sites; this reduces the threshold voltage shift during annealing [4]. The SiO_2 and Er_2O_3 dielectrics exhibited the fading characteristics, but Er_2O_3 has somewhat larger fading values. Large numbers of the charges are trapped in both the gate dielectric and at the interface in the Er_2O_3 NürFETs. Thus, it may be usual to observe higher recombination of the trapped charges. In addition, the higher fading values of device also demonstrate that the numbers of the shallow trap states of Er_2O_3 dielectrics are relatively higher than in the SiO_2 dielectric.

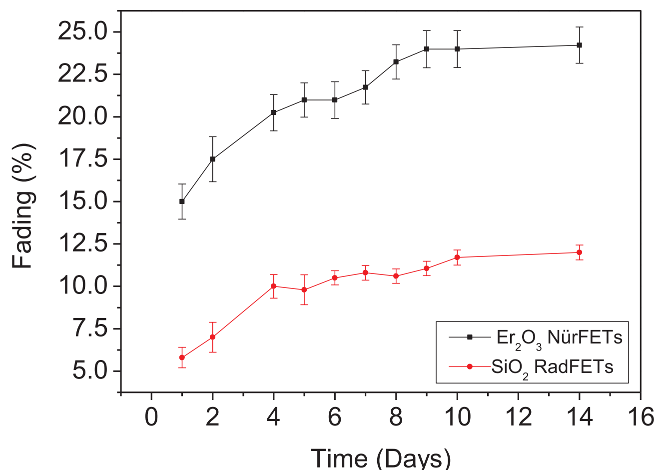


Fig. 6. The post-irradiation fading values of the Tyndall RadFETs and Er_2O_3 NürFETs.

4. Conclusion

The sensitivity of the Er_2O_3 NürFETs has been calculated to be 15 mV/Gy vs. only 4.6 mV/Gy for SiO_2 RadFETs at 30 Gy. However, device sensitivities drop to 2.10 mV/Gy for Er_2O_3 NürFETs, and 1.88 mV/Gy for SiO_2 RadFETs at 1600 Gy. The increased sensitivity in Er_2O_3 samples is associated with higher Z_{eff} number, higher density, and domination of single type of hole trapping mechanism. After 14 days room temperature annealing, 11.9% and 24.4% fading was observed in SiO_2 RadFETs and Er_2O_3 NürFETs, respectively. This higher fading value for the Er_2O_3 is associated with a higher density of generated shallow traps in the Er_2O_3 dielectric. These obtained results have demonstrated that the performance of Er_2O_3 as the gate dielectric in the pMOS dosimeter is advantageous, or at least comparable to that of typically used SiO_2. Higher sensitivity of Er_2O_3 devices is crucial for improved performance of the pMOS dosimeters, particularly at lower doses. In other words, it seems that minimum detectable dose can be improved by using the Er_2O_3 dielectric layer, which can be a milestone for the pMOS dosimeters use in personal dosimetry.

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