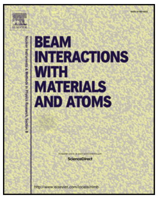
Nuclear Inst. and Methods in Physics Research B 430 (2018) 36–41

Contents lists available at ScienceDirect

Nuclear Inst. and Methods in Physics Research B

journal homepage: www.elsevier.com/locate/nimb



FET-based radiation sensors with Er_2O_3 gate dielectric

S. Kaya[a,b,*], A. Jaksic[c], R. Duane[c], N. Vasovic[c], E. Yilmaz[a,b]

[a] Center for Nuclear Radiation Detectors Research and Applications, AIBU, 14280 Bolu, Turkey
[b] Physics Department, Abant Izzet Baysal University, 14280 Bolu, Turkey
[c] Tyndall National Institute, University College Cork, Ireland

ARTICLE INFO

Keywords:
Erbium oxide (Er_2O_3)
High-k materials
Irradiation effects
Gamma-ray
Charge trapping
pMOS dosimeters

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

---

[*] Corresponding author at: Center for Nuclear Radiation Detectors Research and Applications, AIBU, 14280 Bolu, Turkey.
E-mail address: senolkaya52@gmail.com (S. Kaya).

https://doi.org/10.1016/j.nimb.2018.06.007
Received 22 February 2018; Received in revised form 22 May 2018; Accepted 8 June 2018
0168-583X/

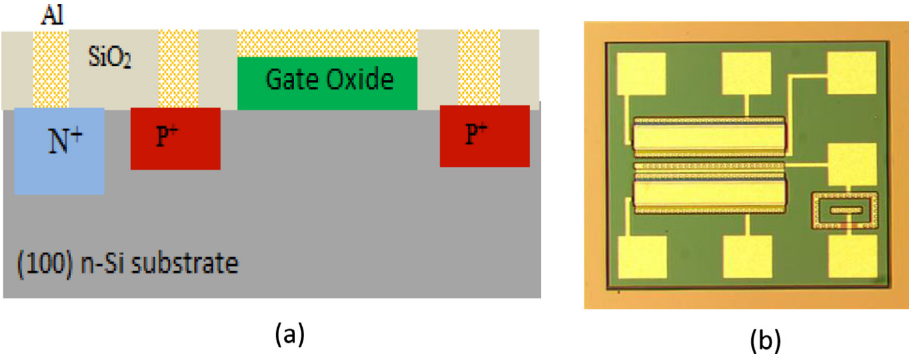


Fig. 1. Fabricated NürFETs (a) schematic cross section, and (b) images under metallurgical microscope.

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 ultrapure 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