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# EVALUATION OF THE RadFET RADIATION SENSOR PERFORMANCE IN 18 MV-EXTERNAL BEAM

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**Abstract:** The radiation response of RadFET irradiated with 18 MV X-rays emitted from a linear accelerator was examined on threshold voltage shifts and trap densities. The measured threshold voltages were compared before and after irradiation. Trap densities calculated using various techniques in the gate oxide and oxide/silicon interface were interpreted. The $\Delta V_{th}$ – D graph showed excellent linearity of up to just about 2 Gy. The RadFETs response to radiation started to deviate from linearity after 2 Gy due to increasing oxide trapped charges induced by electric field screening. The experimental outcomes are in good accordance with the fitting function given for RadFETs. Fixed and switching traps formed by irradiation were investigated. The density of the fixed traps was significantly higher than the density of the switching traps. From the threshold voltages measured under zero gate voltage in a certain time interval, the percentage fading range was calculated as 0.004-1.235%.

**Keywords:** RadFET, Radiation Response, Radiotherapy

**18 MV-Harici Demet ile RadFET Radyasyon Sensörü Performansının Değerlendirilmesi**

**Öz:** Lineer hızlandırıcıdan yayılan 18 MV'luk X-ışınları ile ışınlanan RadFET'lerin radyasyon cevapları, eşik voltaj kaymaları ve tuzak yoğunlukları üzerinden incelenmiştir. Işınlamadan önce ve sonra eşik voltajları ölçülerek karşılaştırılmıştır. Çeşitli teknikler kullanılarak kapı oksitinde ve oksit/silikon arayüzeyinde hesaplanan tuzak yoğunlukları değerlendirilmiştir. $\Delta V_{th}$ – D grafiği, yaklaşık 2 Gy'e kadar mükemmel doğrusallık göstermiştir. RadFET'in radyasyon cevabı, elektrik alan perdelemesi tarafından uyarılan oksit tuzak yüklerinin artmasıyla 2 Gy sonrasında doğrusallıktan sapmaya başlamıştır. Deneysel sonuçlar, RadFET'ler için verilen fit fonksiyonuyla iyi bir uyum içindedir. Işınlama sonucunda oluşan sabit ve anahtarlama tuzakları incelenmiştir. Sabit tuzakların yoğunluğu, anahtarlama tuzaklarının yoğunluğundan önemli bir miktar daha yüksek olarak bulunmuştur. Sıfır kapı voltajı altında ölçülen eşik voltajlarından yüzde zayıflama aralığı %0.004 – %1.235 olarak hesaplanmıştır.

**Anahtar Kelimeler:** RadFET, Radyasyon Cevabı, Radyoterapi

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## 1. INTRODUCTION

The electrical characteristics of the metal/oxide/semiconductor field effect transistors (MOSFETs) such as threshold voltage and transconductance vary under the ionizing irradiation and high electric field strength. For the immobility and sensitivity of the transistor against the stress (radiation, high electric field), it is necessary to know the defect behaviors at the gate oxide, and at the interface of the oxide/substrate. The midgap-subthreshold technique (MGT) and the charge-pumping technique (CPT) are used in the electrical characterization of the MOSFETs. Trap densities formed in the gate oxide (called fixed traps) and at the vicinity of the oxide/substrate interface (called switching traps) can be measured with the MGT, while the trap density composed in the $SiO_2$/Si interface (called interface traps) can be determined by the CPT (Vasovic and Ristic, 2012; Pejovic, 2017).

The radiation sensitive field effect transistors (RadFETs), which are known as p-channel MOSFETs or pMOS dosimeters, are known to be used for dose measurement in a diversity of areas such as space, nuclear and medical. The electron-hole pairs generated in the gate oxide induced by radiation form oxide and interface trapped charges. These created additional charges to production origin charges lead to the threshold voltage shift. The working principle of a RadFET can be summarized in this way. The task of the RadFETs is to transform the absorbed radiation dose to the threshold voltage shift. RadFETs have many advantages over traditional dosimetry, such as instantaneous and non-detrimental read-out, practical calibration, acceptable sensitivity and replicability, tiny volume and lightweight, stability and correctness (Ristic et al., 1996; Holmes-Siedle and Adams, 1986).

Stability after irradiation and high sensitivity to radiation are the expectations that a RadFET using as a dosimeter has to meet. The long-term storage of dosimetric information is expressed with stability. Stability can be explained by the fact that there is no significant change in the threshold voltage shift of the radiated RadFET over a long period of time. The sensitivity of RadFETs and the conservation of dosimetric information are followed up by using the threshold voltage shift obtained from the experimental data such as radiation dose and annealing time (Martinez-Garcia et al., 2015; Fröhlich et al., 2013).

The switching traps density ($N_{st}$) of RadFET with a gate oxide of 400 nm thickness was found to be 1.8 $x10^{10}$ $cm^{-2}$ when measured by MGT, but 1.75 $x10^{9}$ $cm^{-2}$ as calculated by CPT. The fixed traps density ($N_{ft}$) determined using the MGT for the same RadFET is 4.8 $x10^{10}$ $cm^{-2}$ (These values were obtained after 35 Gy gamma-ray irradiation emitted by $^{60}$Co source). The dosimetric information loss was found to be 25% at the long period of 5232 h (Pejovic et al., 2012). Additionally, RadFETs were previously tested with 6 MV X-rays and 10 – 18 MeV electrons at Yilmaz et al. (2017), and similar parameters were investigated. Unlike the publication in Pejovic et al. (2012); Yilmaz et al. (2017), 18 MV X-rays was used for the irradiation test in our study. It is aimed to examine the effects of this irradiation on RadFET characteristic by comparing the same parameters. This article offers an analysis of processes (such as density changes of fixed and switching traps) that affect threshold voltage variation during 18 MV X-rays irradiation without applying any external voltage at room temperature.

## 2. MATERIAL and METHOD

Al-gate pMOS dosimeters used in this study were produced and purchased from the *Tyndall National Institute, Cork, Ireland*. A chip is formed with four RadFETs. These RadFETs are grouped in pairs according to channel widths and channel lengths. RadFETs with a 300 µm (channel width)/50 µm (channel length) were called R1 and R3, while those with a 690 µm (channel width)/15 µm (channel length) were called R2 and R4. A Reader Circuit (RC) for read-out the RadFETs is obtained by connecting the source, drain and gate terminals of R1 and R2 independently and connecting the source-bulk and gate-drain terminals of R3 and R4 to each other.

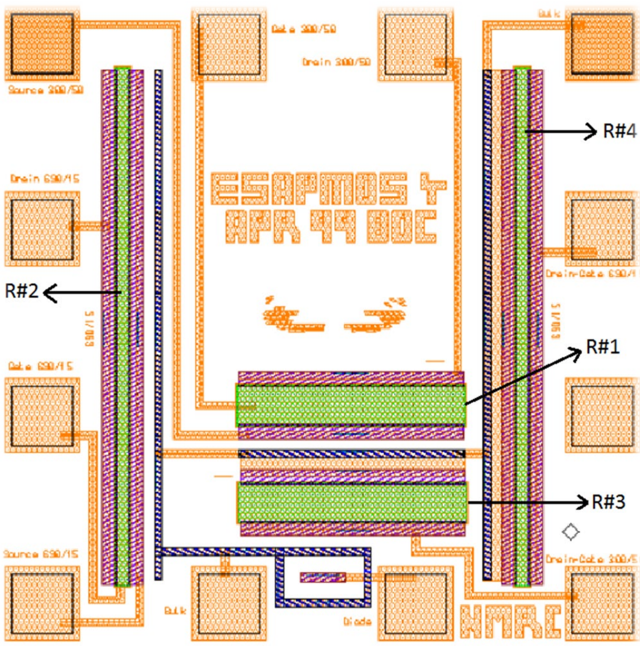


***Figure 1:***
*Top view of the RadFET chip composed of four individual RadFETs (Andjelkovic et al., 2015)*

Measurements were taken from R1 at room temperature. RadFETs with a 400 nm thick gate oxide layer have been chosen for 18 MV X-ray irradiation due to their high sensitivity and good linearity (Yilmaz et al., 2017). 18 MV X-ray irradiation was done with LINAC which is used regularly in the "*Ankara Atatürk Research and Training Hospital*" oncology department. The RadFETs were put in a water-equivalent phantom before irradiation. This phantom is 0.3 x 0.3 x 0.1 $m^3$ in size, white polystyrene RW3 type SP34 solid phantom. The dose was controlled with the IBA-FC65P ionization chamber. The depth at which the maximum dose between the RadFET and the phantom surface was obtained is 0.03 m. For irradiation, the RadFET was positioned at 1 m from the source and the irradiation area was chosen as 0.1 x 0.1 $m^2$ (Yilmaz et al., 2017). The RadFETs were irradiated with 20 Gy for RC measurement, 66 Gy for charge analysis caused by radiation and 92 Gy for fading evaluation using 18 MV X-ray under zero gate bias. The threshold voltage was determined as the voltage corresponding to 10 µA.

Electrical characteristics in the result of irradiation are measured using a sourcemeter and a pulse/function generator. For practicality, the threshold voltage shifts of the RadFETs have been assessed using the RC configuration. I-V measurements were made using MGT and CPT. With this measurement, it is aimed to characterize the traps caused by radiation. The fading characteristic was recorded at room temperature for the 1620 s.

As a result of the interaction of radiation, MGT and CPT techniques were used to determine the trap density of charges inside the oxide and oxide/silicon interface (McWhorter and Winokur, 1986; Brugler and Jespers, 1969; Paulsen and White, 1994). The traps that do not replace charges with silicon substrate are called fixed traps (FTs) and they are located within the gate oxide. Switching traps (STs) are exchanging charge with silicon substrate throughout measurement. STs are divided into slow switching traps (SSTs) and fast switching traps (FSTs) depending on their switching characteristics. SSTs are located in the oxide close to the $Si/SiO_2$ interface, while FSTs are recognize as the real interface traps located much closer to the $Si/SiO_2$ interface. As a result of the calculation with MGT, FT density variation is determined. ST density variation can be calculated using both techniques. In this way, contributions can be determined for two types of traps. Sub-threshold I-V curves and the parallel shift of Elliot curves from the CPT are caused by the FTs (Lu et al., 2011). The STs provide stretch-out of sub-threshold curves in MGT and increase of charge pumping current ($I_{CP}$) in CPT. MGT can perceive SSTs and FSTs as separate STs. CPT can define FSTs and fastest SSTs as STs. This is the main difference between MGT and CPT. The $N_{st}$ density calculated by CPT is very close to that calculated by FSTs. Therefore, $N_{st}$ is calculated with MGT. For MGT and CPT, $N_{st}$ values calculated using the equations given in Ristic (2009); Stamenkovic et al. (2014) are discussed. CPT from Groeseneken et al. (1984) was used for absolute switching oxide trap density. The threshold voltage shifts are divided into total doses to find the sensitivities of the sensors. Dosimetric information loss caused by self-annealing at room temperature is explained as fading/threshold voltage recovery. It is calculated by the equations given in the Ristic et al. (1996) and Pejovic et al. (2012).

## 3. RESULTS and DISCUSSION

The threshold voltage shift ($\Delta V_{th}$) caused by the 18 MV X-rays is shown as a function of the cumulative dose in Figure 2. The fitting coefficients x, y, and z were calculated using the following relationship between the $\Delta V_{th}$ and the applied dose (D) (Yilmaz et al., 2017; Ristic et al., 2011; Ristic et al., 2015):

$$\Delta V_{th,ft,st} = x - \frac{x}{1 + yD^{z}} \quad (1)$$

The values of these coefficients are given in Figure 2. The obtained $R^2$ value from Equation 1 for the 18 MV X-ray is 0.9993. The RadFET sensitivity increases with the decreasing dose. The radiation response of the RadFET is expected to be linear at low dose levels (Holmes-Siedle et al., 2007). $\Delta V_{th}$ is linear at low doses ($R^2$ value is 0.9986) and deviates from the linearity at higher doses as seen from the Figure 2. The deviation is caused by the electric field screening (Yilmaz et al., 2017). The RadFET sensitivity was calculated to be 26.7 mV/Gy for 20 Gy dose while it is about 55.0 mV/Gy in the linear region. The result shows that the sensor sensitivity is consistent with the values obtained for 6 MV X-rays (Yilmaz et al., 2017). Jaksic et al. (2002) irradiated RadFET (400 nm gate oxide thickness) with $^{60}Co$ source in their related study.

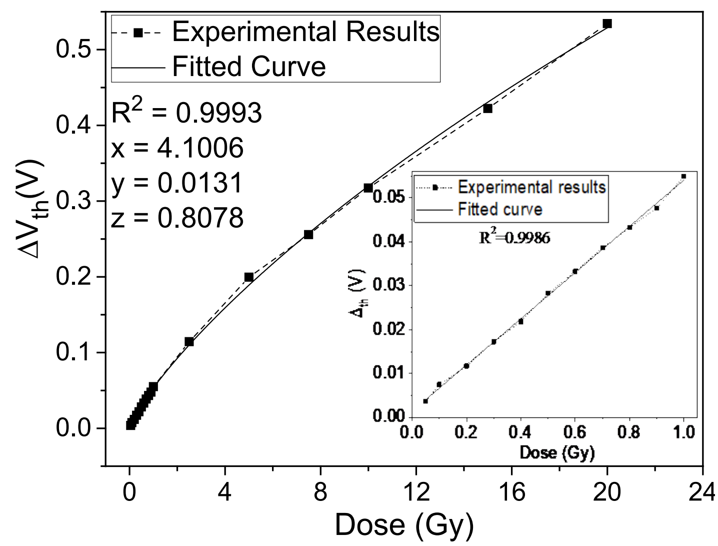


***Figure 2:***
*The threshold voltage shift in RadFET for 18 MV X-rays*

RadFET sensitivity from this study was obtained as approximately 58 mV/Gy for 20 Gy (Calculation belongs to us). The higher sensitivity is due to the fact that the gamma energy of 1.25 MeV is more likely to interact with the material compared to X-rays of 18 MV. In the study of Ristic et al. (2011), the sensitivity of RadFET (100 nm gate oxide thickness) irradiated with $^{60}Co$ source was calculated as ~2.5 mV/Gy for 20 Gy (Calculation belongs to us). The lower sensitivity of RadFET compared to this study may be explained by the thinner sensitive region thickness. To improve sensor sensitivity, stack RadFET with two-layer gate oxide designs by Ristic et al. (1997) or design of stacked RadFET by O'Connell et al. (1996, 1999) may be a good solution.

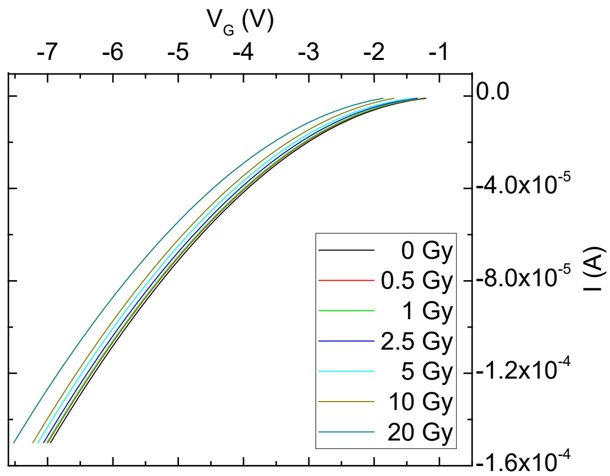


***Figure 3:***
*I-V characteristics varying with irradiated dose*

The variation in I-V characteristics are given in Figure 3. As the irradiated dose increased, the curves shifted to the left. The modifications of the density of FTs ($\Delta N_{ft}$) are shown in Figure 4. The increased radiation dose causes more electron-ion pairs to be formed in the environment. Since the mobility of the positive charges is higher than that of the negative charges (such as electrons), they are more likely to be trapped in the oxide layer. The increase of the trapped charges inside the oxide layer/the density of the FTs also increases the amount of shift in the threshold voltage.

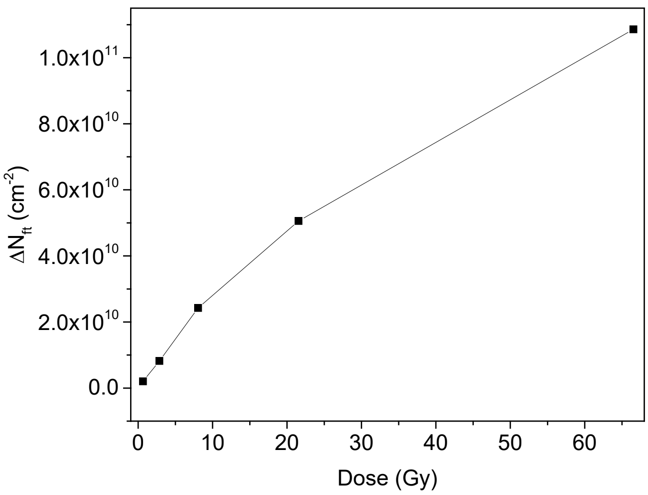


***Figure 4:***
*The areal density changes of fixed traps ($\Delta N_{ft}$) in RadFET irradiated by 18 MV X-rays*

The modifications of the areal density of STs ($\Delta N_{st}$) are given in Figure 5 for CPT and MGT, respectively. As can be seen in Figure 5, the values measured with MGT are higher than those measured with CPT for all doses. The difference between the values calculated by MGT and CPT may be due to diversity in used frequencies. The used frequency in the MGT is a little Hz, while the effective frequency in the CPT is 100 kHz (Stamenkovic et al., 2014). Sensitivity to interface traps is quite high in MGT and CPT. However, the CP signal is sensitive only to fast switching traps. With the MG signal, both fast and slow switching traps can be followed. Moreover, the underside of the silicon band gaps was scanned with the MGT, while the centers were also scanned by the CPT. As a result, it is natural that $\Delta N_{st}$ (CPT) is lower than $\Delta N_{st}$ (MGT) because the edges of the band gaps cannot be reached by CPT.

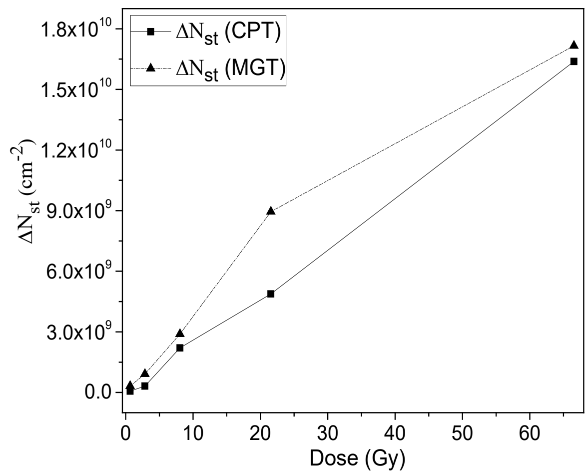


***Figure 5:***
*The areal density changes switching traps ($\Delta N_{st}$) for CPT and MGT in RadFET irradiated by 18 MV X-rays*

Observing the threshold voltage shifts, it is clearly noticed that the FT contribution is higher than the ST contribution. FT/ST rates for each dose (0.65 Gy, 2.85 Gy, 8.05 Gy, 21.55 Gy, and 66.55 Gy) were calculated as 6.35, 8.99, 13.20, 30.70 and 10.90, respectively. It is also seen with the data that FTs are generated faster when compared to STs (Ristic et al., 2011).

The fading values of the RadFETs were calculated under zero gate bias at room temperature after an accumulated dose of 92 Gy. After 1620 s, 18 MV X-ray irradiation, the fading characteristics are presented in Figure 6. The percentage fading (f%) range is 0.004 – 1.235. The decreased oxide trapped charge density due to the tunneling of electrons with irradiation may allow the threshold voltage to have a smaller negative value. This situation affects the fading process and the fading takes a positive value. The f% value at the 150 s is negative (-0.059%), since the threshold voltage shifts to the higher negative voltage values. The probable cause of this situation is the increases in the interface trapped charges density during the fading period and, accordingly relatively slow annealing of the oxide trapped charges. However, the fact that all fading values were positive except for 150 s indicates that oxide trapped charges more dominant role in this process (Yilmaz et al., 2017). Negative values were also observed in the short-term fading characteristics of the RadFETs with the gate oxide layer thickness of 1 µm as a result of irradiation with 6 MV radiotherapic beam (18.09 Gy and 30.04 Gy) (Martinez-Garcia et al., 2015). In contrast, all values were positive in the short-term fading characteristics of RadFETs (with the gate oxide layer thickness of 400 nm) 6 MV X-rays and 10 – 18 MeV electron beams in the study by Kahraman et al. (2015).

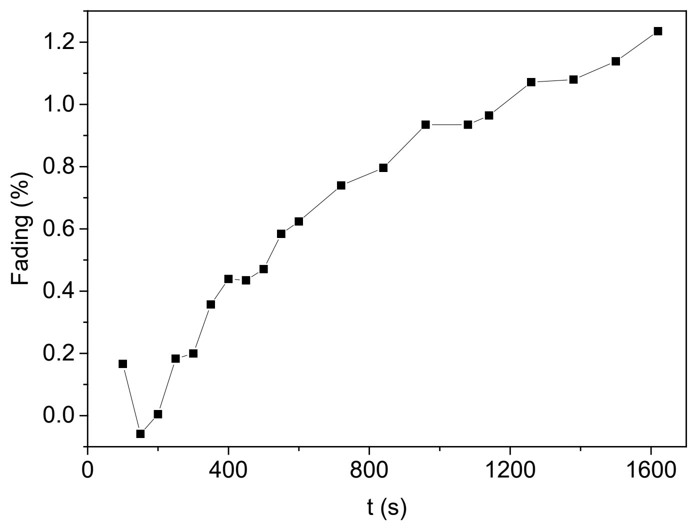


***Figure 6:***
*1620 s (short-term), post-irradiation fading characteristics*

## 4. CONCLUSION

The sensitivity and trap densities of RadFETs were examined after 18 MV X-rays irradiation. The threshold voltage shift across the given dose exhibited an ideal linearity, especially in small doses. Sensitivity for a 20 Gy dose was found 26.7 mV/Gy. The short-term fading characteristics, which are taken from 100 s to 1620 s, show a tendency towards positive value, which indicates that this process is managed by oxide trapped charges rather than interface trapped charges. The radiation responses in the working dose range of the RadFETs indicated the expected electrical characteristic. Applications such as using of different gate oxide layers, designing of the sensors as stack structure can be made to improve sensitivity of RadFETs to low doses.

## ACKNOWLEDGMENT

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