ESA-QCA00136-R93

Investigation into the re-use of PMOS Dosimeters[1]

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Abstract

Radiation sensitive field effect transistors have applications as integrating dosimeters in spacecraft, laboratories and medicine to measure the amount of radiation dose absorbed. However these dosimeters can measure only to a maximum dose which is determined by the type and sensitivity of the RADFET being used. On reaching the maximum radiation dose these dosimeters are usually replaced. The aim of this paper is to investigate the possibility of reusable dosimeters which to-date has not been addressed in the published literature. This study examines the response of dosimeters which were irradiated, annealed back to their original pre-irradiation threshold voltage and then irradiated for a second time. The results of the second irradiation suggest that re-using PMOS dosimeters is a feasible option.

I. INTRODUCTION

The concept of a pMOS dosimetry is based on the build-up of positive oxide charge in the gate region of a p-type MOSFET when it is exposed to ionising radiation. The increase in the oxide charge causes the MOSFET's threshold voltage to change and this change in threshold voltage is then used to estimate the absorbed dose[1]. The basic mechanisms for the build-up of trapped oxide charge and interface traps with dose are widely discussed in the literature[2-4] and are not outlined here. PMOS dosimeters are also referred to as RADFETs which is an acronym for `RADiation sensing Field Effect Transistors'[5].

The dynamic range of the RADFET is defined to be the number of decades between the smallest detectable dose and the dose at which saturation of the build-up of oxide charge reduces the sensitivity below that suitable to a specific application. The dynamic range of the RADFET may be changed by changing the oxide thickness, the oxide processing and the bias during irradiation. However these changes also change the sensitivity of the RADFET. The sensitivity required of a RADFET depends on its application. RADFETs have applications in the high dose range from 10^3 to 10^7 rad in nuclear facilities. In order that the dynamic range of the dosimeter is sufficient to measure the maximum dose, zero bias irradiation is used. Another high dose application of RADFETs is the use of dosimeters in space. Depending on the location, time and duration of the mission the RADFET will be expected to measure from 10 rad to 0.5 Mrad. The RADFET has been successfully used in satellites and is a reliable sensor for sending back information on the total dose being absorbed by electronics in the spacecraft[6]. However when saturation of the build-up of trapped oxide charge takes place, then the RADFET is no longer operational as a dose meter and no further information is available on the total dose radiation environment. This is of critical importance to total dose monitoring on-board spacecraft because it then impossible to estimate the end-of-life of the on-board electronics if no measure of the absorbed dose is available. Thus the possibility of erasing the effects of the absorbed dose from the dosimeter and re-using it to extend its operational lifetime is particularly attractive for satellite applications.

When the dosimeter is removed from the radiation environment, relaxation of the threshold voltage takes place with time and is referred to as fading. The fading may be either positive or negative depending on the relative build-up of interface traps and the annealing of trapped holes. Fading was previously investigated for the NMRC's pMOS dosimeter and is was shown that the fading was dependent on the anneal time and temperature[7,8]. For 100°C annealing with 5 V applied to the gate, up to 65% fading was measured in the RADFETs after 280 hours. Following on from the fading experiments[7] this paper examines the possibility of extending the fading concept so that 100% fading may be achieved. At 100% fading the threshold voltage of the RADFET has returned to its pre-irradiation threshold voltage. The work then investigates the possibility of re-using the fully annealed RADFET and the response of the RADFET during the second irradiation is found to be lower than that of the first irradiation. The causes of the lower sensitivity during the second irradiation are discussed. The possibility of re-using pMOS dosimeters was not addressed previously in the published literature and the results of these experiments show that it is a viable option and contribute a positive first-step towards dosimeters with extendible operational lifetimes.

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[1] This work was sponsored and technically supported by the European Space Agency as part of the MTSL-01 work programme.

0-7803-1793-9/$4.00©1994IEEE

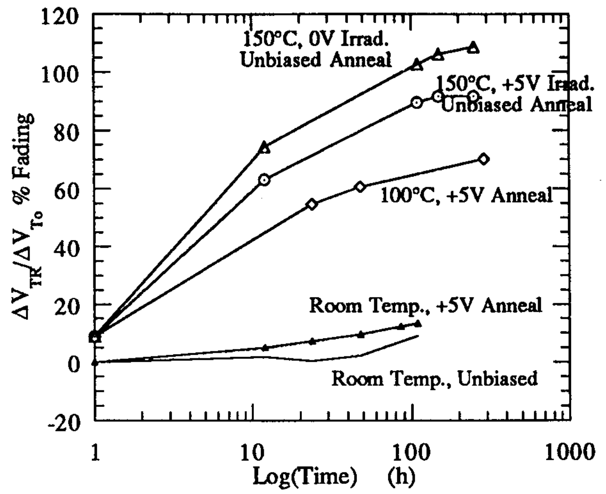

Figure 1. Fading in PMOS dosimeters as a function of anneal time for different anneal temperatures. The 150°C anneal was unbiased and the samples were irradiated with either zero bias or 5 V applied to the gate, the 100°C anneal samples had 5 V anneal bias and the room temperature anneal was carried out with and without bias. The high temperature anneals were performed subsequent to the 576 hours room temperature anneal.

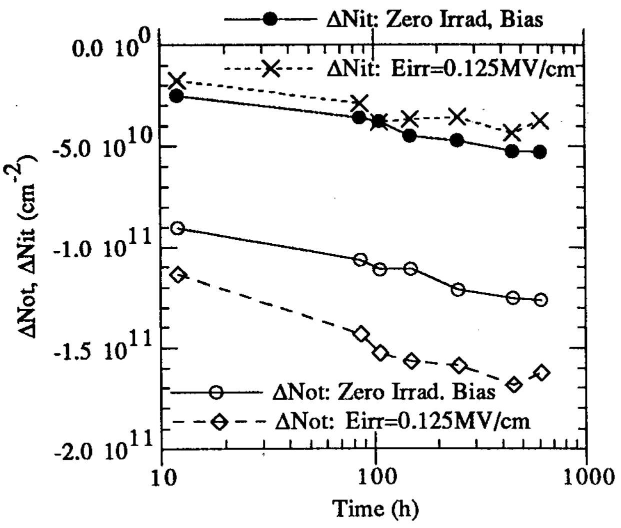

Figure 2. Change of trapped oxide charge and interface trap charge as a function of anneal time for pMOS dosimeters annealed with zero bias at 150°C. The samples were irradiated with either zero bias or 5 V to 40krad(H_2O) prior to the 150°C anneal.

II. EXPERIMENTAL

Standard NMRC's dosimeters fabricated using a metal gate PMOS technology were used. The technology has a 400 nm gate oxide gate consisting of a dry/wet/dry sandwich. The samples were irradiated using the ^{60}Co radiation source at ESTEC to a maximum of 40 krad(H_2O) using a dose rate of 45 rad(H_2O)/min. One set of dosimeters were irradiated with +5 V on the gate and the other terminals grounded. The remaining samples were irradiated with all RADFET terminals grounded. Subsequent to the first irradiation the fading of the dosimeters was examined at room temperature for 576 hours. One set of the dosimeters were annealed at 100°C for 280 hours with a bias of 5 V on the gate. The remaining dosimeters along with unirradiated control dosimeters were then subjected to a 150°C unbiased oven anneal (with all terminals shorted) until saturation of the annealing of the threshold voltage of the irradiated dosimeters began after 576 hours. The samples were then irradiated for the second time using conditions identical to the first irradiation.

The transfer characteristics of the dosimeters were measured as a function of dose and time. All measurements on the dosimeter samples annealed at 150°C were carried out by interrupting the anneal and performing them at room temperature. Charge separation techniques[9] were used to obtain the change in the oxide charge and interface trap charge as a function of dose and anneal time.

The most convenient method used in measuring the shift in threshold voltage is to bias the RADFET in saturation, with gate and drain grounded, and using a constant drain current I_{DS}, measure the source voltage V_O required to give that current[8], as a function of dose. The shift in V_O approximates the change in the threshold voltage and is the dosimetric parameter. This biasing configuration is normally referred to as the dosimeter reader circuit. However upon power-up of the circuit, the output voltage, V_O, drifts with time due to the threshold voltage of the RADFET drifting with time. This affect is caused by charge perturbations in the oxide[10].

III. EXPERIMENTAL RESULTS

A. PMOS RADFET Annealing

PMOS RADFETs were examined for their fading as a function of time at room temperature, at 100°C and at 150°C[8]. Figure 1 shows the % fading which occurred in the samples. The % fading is obtained by evaluating the ratio of $\Delta V_{TR}/\Delta V_{To}$, where ΔV_{TR} is the change in the RADFET's threshold voltage with time after irradiation and ΔV_{To} is the change in the RADFET's threshold voltage due to radiation. At 100°C, after 280 hours approximately 65% fading of the shift in threshold voltage due to radiation has occurred. The unirradiated control dosimeters annealed unbiased at 150°C showed no variation in threshold voltage with anneal time.

The dosimeter samples which were annealed at 150°C achieved approximately 100% fading in 100 hours. Figure 1 shows that 92% annealing of the change in threshold voltage due to radiation occurred in the RADFETs which were irradiated with a gate oxide electric field of 0.125 MV/cm (5 V on the gate) and annealed with zero bias at 150°C. The dosimeters which were irradiated with zero bias and annealed at 150°C

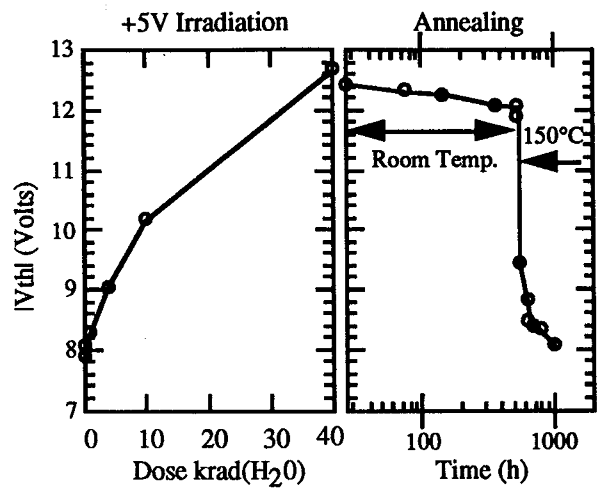

Figure 3. Change in the absolute value of the threshold voltage of the NMRC's pMOS RADFET as a function of dose and subsequent annealing. The dosimeters were irradiated to 40 krad(H_2O) with an oxide field of 0.125 MV/cm (5 V on the gate) and were annealed at room temperature with 5 V on the gate for 576 hours after irradiation. The temperature of the RADFET was then raised to 150°C and the change in the threshold voltage for the 150°C annealing was measured with the dosimeters cooled to room temperature.

with zero bias achieved 106% annealing of the radiation damage, i.e. rebound of the dosimeter threshold voltage took place.

Figure 2 shows the average change in the oxide charge versus post-irradiation anneal time for the dosimeter samples annealed with zero bias at 150°C. The sample-to-sample variation in the change in the oxide charge was less than 10% for all the dosimeters examined. Both the trapped oxide charge and the interface trapped charge decrease, thus the irradiated RADFET threshold voltage returns towards its pre-irradiation threshold voltage. Figure 3 shows the absolute change in threshold voltage for the RADFETs which were irradiated to a dose of 40 krad(H_2O) and annealed for 576 hours at room temperature with 5 V on the gate. The dosimeters were then annealed with zero bias at 150°C until the threshold voltage was approximately equal to the pre-irradiation threshold voltage. For direct comparison with the radiation measurements, the threshold voltage of the dosimeters was measured at room temperature and the heating and cooling steps(~10°C/min) are an integral part of the anneal time. Figure 3 clearly demonstrates that it is possible to return the threshold voltage of the RADFET to its pre-irradiation value when the annealing temperature of the RADFET is raised to 150°C.

B. PMOS RADFET 1^{st} & 2^{nd} Irradiations: a Comparison

After the 150°C anneal the dosimeter samples were re-irradiated with conditions identical to the first irradiation. Figure 4 and 5 show the average threshold voltage change as a function of dose for both the first and the second irradiations of the pMOS

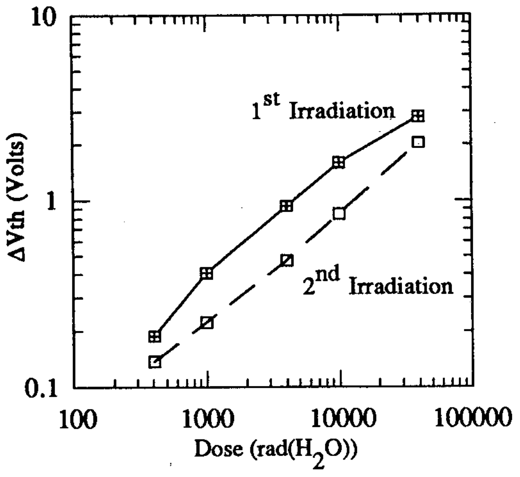

Figure 4. Shift in threshold voltage of pMOS dosimeters versus dose. The dosimeters were irradiated with 0 V on the gate, annealed at 150°C to their pre-irradiation threshold voltage and irradiated for the second time with 0 V on the gate.

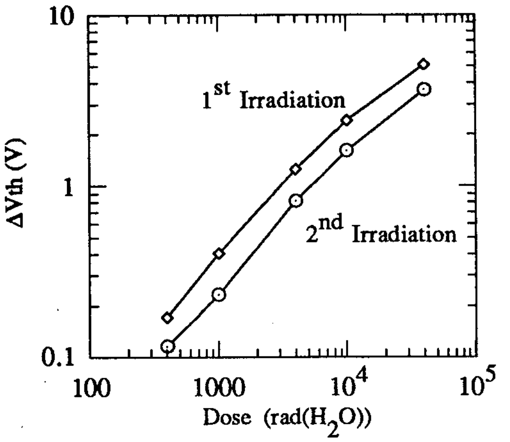

Figure 5. Shift in threshold voltage of pMOS dosimeters versus dose. The dosimeters were irradiated with 5 V on the gate, annealed at 150°C with zero bias to their pre-irradiation threshold voltage and irradiated for the second time with 5 V on the gate.

dosimeters irradiated with zero and 5 V on the gate respectively. The maximum RADFET-to-RADFET variation in both sets of radiation results was less than 10% for all irradiation biases and doses examined. For both sets of samples the radiation response is less for the second irradiation than the first irradiation. Figure 6 shows the build-up of trapped oxide charge and interface trapped charge as a function of dose for both the first and the second irradiation of the RADFETs which were irradiated with 5 V on the gate. The build-up of interface trapped charge is approximately equal for both irradiations and the values obtained at 400 rad(H_2O) and 1 krad(H_2O) are not shown because they were negative but within the

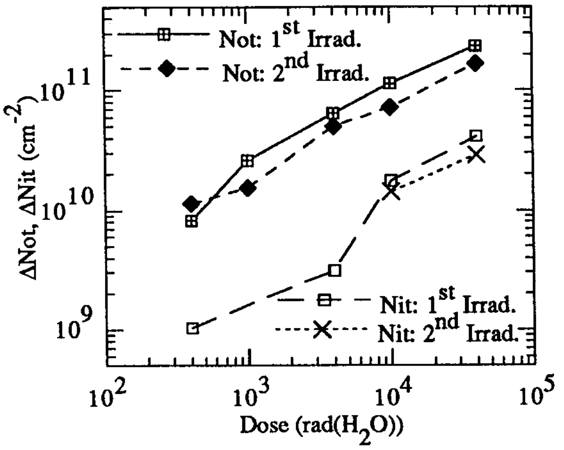

Figure 6. Build-up of trapped oxide charge and interface charge as a function of dose. The pMOS dosimeter samples were irradiated with 5 V on the gate, annealed with zero bias at 150°C to their pre-irradiation threshold voltage and then irradiated for a second time with 5 V on the gate.

experimental error of the measurement system(2.5×10^9 cm^{-2}). The net build-up of trapped oxide charge is less during the second irradiation compared to the first. Similar results were also obtained for the dosimeters which were irradiated with zero bias, annealed at 150°C to their pre-irradiation threshold voltage and re-irradiated for the second time with zero bias on the gate.

In this work the dosimeter threshold voltage drift was examined between 10 seconds and 20 seconds after power up of the reader circuit. The increase in the voltage reading was less than 0.25% of the shift in threshold voltage due to radiation for the samples which were irradiated for the first time. During the 150°C anneal, the 10-20 second drift in threshold voltage returned to the pre-irradiation value of 1mV. The read-time instability increased slightly for the samples which were irradiated for the second time, however the increase in the threshold voltage was less than 0.5% of the shift in threshold voltage due to irradiation, for doses up to 40 krad(H_2O).

IV. DISCUSSION

The results of the fading study[8] on the NMRC's pMOS dosimeter showed that the fading which takes place in the RADFET's threshold voltage is both bias, time and temperature dependent as shown in figure 1. However fading is normally not desirable because it leads to a loss of information about the absorbed dose. However large amounts of fading was found to take place at high temperature[8], during a 100°C anneal the RADFET's threshold voltage had recovered by 65% in 280 hours and during a 150°C anneal approximately 100% fading had taken place after 100 hours. This work investigates a possible advantage of such large percentage fading which occurs at high temperatures, i.e. the possibility of re-using the RADFET as a dosimeter once the radiation damage due to the absorbed dose is annealed out. The results of Ref. [8] also show that fading is dependent on both log(time) and log(temperature). Thus the higher the temperature which the dosimeter is subjected to the shorter the time required to anneal the irradiated RADFET to its pre-irradiation threshold voltage.

The annealing of trapped holes as a function of time and temperature was discussed for the pMOS dosimeter in Ref [8] and may be explained by the combined tunnel and thermal model of McWhorter[11]. Figure 2 shows that the interface traps as well as the trapped holes anneal with time during the 150°C anneal. The NMRC's pMOS dosimeter is fabricated using a metal gate technology and this interface trap annealing may be explained by the active participation of hydrogen during the thermal anneal and thereby passivating the interface dangling bonds[12]. When the oxide is covered by a layer of aluminium it has been found that thermal annealing of the interface traps is equally effective whether or not the ambient contains hydrogen[2,12]. This is attributed to the fact that during a thermal anneal that the aluminium reacts with minute amounts of H_2O on the oxide surface and releases the active hydrogen species which then diffuse to the SiO_2/Si interface and passivate the interface traps[13].

Comparing the change in threshold voltage of the second irradiation to that of the first irradiation, show that for both 0 V and 5V irradiation biases and all irradiation doses that the shift in threshold is less for the second irradiation compared to the first irradiation. The build-up of interface traps is approximately equal for both sets of irradiations, however the build-up of oxide charge is less for the second irradiation compared to the first even though the trapped hole charge due to the first irradiation was completely removed for the zero bias irradiation dosimeters and removed to within 8% for the dosimeters which were irradiated with 5 V on the gate. Longer anneal times or higher anneal temperatures should anneal the theshold voltage of the dosimeters irradiated with 5 V completely to their pre-irradiation value. However more complete annealing is not the limiting factor for repeatibility of the device response to irradiation, because the zero bias irradiation dosimeters whose trapped oxide charge was completely annealed also gave a lower response during the second irradiation compared to the first. These results suggest that some type of 'memory' effect exists from the first irradiation. One possible explanation for this is that 'neutral' electron traps are generated by the radiation. The generation of these traps was first discussed by Aitken and Young[14,15] for electron beam irradiation and X-ray irradiation[16]. However in ^{60}Co irradiation the photons interact primarily by Compton scattering. In the Compton process most of the photon energy is carried away by secondary electrons and almost all the energy is deposited in the SiO_2 by these electrons. Thus from Ref.[15], it is reasonable to assume that γ-rays will also produce neutral electron traps during irradiation. This neutral electron trap has a capture cross-section of the order of 10^{-15} cm^2 for an oxide field of 0.125 MV/cm and requires an anneal temperature in excess of 550°C to reduce its density[2]. The exact chemical nature of these traps is not clear and normally the traps are not visible because a net positive shift in the oxide obscures their presence. The results of figure 6 suggest that the electron traps become evident at doses greater than approximately 1 krad(H2O) and have a value of approximately 7.5×10^{10} cm^{-2} at 40 krad(H_2O) of the second 5 V irradiation. At low doses, less than 1 krad(H_2O), this build-up is less than 10^{10} cm^{-2}. This suggests a trapping within the oxide which increases with dose rather than a limitation of the trapping due to some structural or chemical changes of the hole traps in the oxide being irradiated for the second time. If such a change were to take place in the oxide due to a combination of the first irradiation and the 150°C temperature anneal then the effect should be similar both at low and high doses. In conjunction with the neutral electron traps being formed during the first irradiation they are also forming during the second irradiation so essentially at 40 krad(H_2O) of the second irradiation the 7.5×10^{10} cm^{-2} electron traps measurable may be attributed to both irradiations(no reduction is expected due to the 150°C anneal). No estimation of the actual density of neutral electron traps in the oxide is available and would require avalanche electron injection to measure the traps[14]. The difference in the net density of hole traps at 40 krad(H_2O) of the second irradiation compared to the first was 3.7×10^{10} cm^{-2} for the dosimeters which were irradiated with zero bias on the gate. Thus the effective difference between the response of the first irradiation and the second irradiation is dependent on the irradiation electric field which is applied to the oxide. This agrees with the theory that the difference in the response is due to additional bias dependent electron trapping present during the second irradiation.

The reduced sensitivity of the RADFETs coupled with the increase in threshold voltage drift during the second irradiation could also be attributed to the presence of additional "border traps" during the second irradiation compared to the first irradiation. The effect of border traps on MOS devices was discussed in detail by Fleetwood et al.[17]. In Ref. [17] border traps are described to be the near interfacial oxide traps which may exchange charge with the Si during the time scale of the measurements. These traps are designated type-1, type-2 and type-3. Border traps type-1 and 2 are donorlike and involve an electron which "compenstates" the charge on a trapped hole. Trap type-3 is amphoteric in which the associated hole or electron may be exchanged with the Si bulk. Upon biasing the dosimeter reader circuit, the threshold voltage increases with time, which means that the positive charge in the oxide is increasing. The drift is greater during the second irradiation of the RADFET, however the interface trap build-up during the second irradiation is approximately equal to that of the first irradiation, (figure 6), indicating that fast interface traps are not contributing to the increased drift. This suggests that that the oxide border traps are greater during the second irradiation. However border trap type-3 is positive for p-type devices and if this trap is increased during the second irradiation then it would lead to an overall increase in sensitivity compared to the first irradiation which is not the case. Fleetwood et al.[17] showed that when 45 nm oxides are subjected to negative bias annealing immediately after irradiation the negatively charged border traps anneal and thus causes an increase in the positive charge in the oxide. When the dosimeter is biased in the reader circuit the electric field across the oxide is negative and the increase in drift in the dosimeter threshold voltage with time is consistent with the annealing of negatively charged traps in the oxide. The increased presence of such negatively charged border traps during the second irradiation also agrees with the reduced radiation sensitivity compared to the first irradiation.

However these negatively charged border states are described to involve an electron that "compensates" the charge of a trapped hole[17]. The results of Ref.[17] showed that the gain and loss of these compensating trapped electrons agree with the published results on the reversability of trapped hole annealing. Schwank et al.[18] showed that on applying a negative bias at 100°C it was possible to recover some of the annealed trapped oxide charge. The existence of this reversible annealed charge was investigated as part of the NMRC RADFET fading study[8]. The dosimeters which were annealed at 100°C were examined for reverse annealing and did not exhibit any recovery of the annealed oxide charge which indicates that the annealing of the trapped charge is permanent and that border traps do not exist after the anneal. The increase in dosimeter threshold voltage drift-up during biasing and reduced sensitivity during the second irradiation suggests a greater density of border traps during the second irradiation. However the complete annealing of the trapped hole charge from the first irradiation may have caused the hole trap sites in the oxide to reorganize so that during the second irradiation the existence of border traps associated with trapped holes is more enhanced compared to the first irradiation.

Fleetwood et al. [19] cycled 350 nm soft oxides through x-ray irradiation to 5 krad(SiO_2) and Thermally Stimulated Current (TSC) measurements four consecutive times and the results indicated that no significant permanent damage to the device occurred due to either TSC measurements or due to irradiation. However the maximum temperature reached during the TSC measurements of the 350 nm oxide in Ref. [19] was 350°C with an applied bias of -30 V and the total cumulative dose received was only 20 krad(SiO_2). These results suggest that annealing of the irradiated 450 nm dosimeter oxide at higher temperatures with a large reverse bias needs to be investigated for its effect on the annealing of both trapped positive and negative charge in the oxide and thus its effect on device repeatibility.

Thus the overall effect of re-using the oxides is that the dosimeter being irradiated for the second time has a lower shift in threshold voltage with dose and thus the RADFET has a lower radiation sensitivity during the second irradiation. However within the scope of these experimental results it is not possible to specifically attribute the increased negative charge(reduced net positive oxide charge) during the second irradiation to either the generation of neutral electron traps during irradiation or to the generation of a higher density of border traps during the second irradiation. It is possible that the reduced sensitivity during the second irradiation may be a combination of both of these effects. For the dosimeters which were irradiated with 5 V on the gate the sensitivity was reduced by 20% at 40 krad(H_2O) and by 27% at 40krad(H_2O) for the dosimeters which were irradiated with zero bias on the gate. Apart from this lowering of RADFET sensitivity the results of this study show that the dosimeter response of the second irradiation compares quite favourably to that of the first irradiation. The annealed RADFET's sensitivity may be calibrated and then used to predict the absorbed dose during the second irradiation. The fading and read-time stability of the second irradiation are similar to the first irradiation which makes the RADFET suitable to act as a dosimeter for a given application but with lower radiation sensitivity. In this work only unbiased 150°C annealing was examined. However Fleetwood et al.[20] have showed that "Radiation Induced Charge Neutralization"(RICN) occurs by the reversal of the gate bias during irradiation. Complete RICN was not achieved for the p-channel devices in Ref.[20]. However a combination of the reversal of the gate bias during a high temperature anneal when taking place in a radiation environment should allow annealing within the dosimeter at shorter times than in this work. This needs to be investiaged as part of developing a re-usable dosimeter however these results show that annealing an irradiated RADFET to its pre-irradiation threshold voltage and re-using it as a dosimeter is a viable option and are a positive first step towards obtaining pMOS dosimeters with an extendible operational lifetime. One major application of such a RADFET is satellite applications. The localized heating of RADFETs and the feasibility of re-using such RADFETs is currently the topic of another investigation at the NMRC[21], and to maintain the RADFET at 150°C requires a power consumption of 1.5 Watt for the duration of the anneal.

V. SUMMARY/CONCLUSIONS

In this work we investigate the possibility of re-using PMOS dosimeters by annealing irradiated dosimeters to their pre-irradiated threshold voltage at 150°C and irradiating them for the second time. The results of the second irradiation compare quite favourably with the results of the first irradiation, however the radiation sensitivity of the RADFET during the second irradiation is less than that of the first irradiation. This lower sensitivity is due to a lower build-up of net positive charge in the gate oxide during the second irradiation and the causes of this lower build-up of trapped oxide charge is attributed to either neutral electron traps being generated in the oxide during irradiation or increased generation of border traps during the second irradiation. The ability to re-use PMOS dosimeters is particularly suited to applications such as spacecraft where it is not always feasible to replace the dosimeter once saturation has taken place in the oxide or the maximum dose measurable by the dosimeter set-up is reached. In this case the dosimeters could be annealed on-board and be re-used to extend the measurement life of the dosimeter unit.

VI. ACKNOWLEDGEMENTS

The authors thank Bengt Johlander and Bob Nickson of ESTEC for their advice and assistance with this project.

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