ESA-QCA00144-R95

Stacked RADFETs for Increased Radiation Sensitivity.

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Abstract

Hitherto, pMOS Radiation Sensitive Field Effect Transistors (RADFETs) have not been able to detect doses in the milli-rad range, which are required for low dose clinical/personnel applications. This paper reports on further investigation of a design approach, where RADFETs are connected in a stacked sequence so that increased radiation sensitivity is obtained. The radiation sensitivity obtained for 40 stacked RADFETs is approximately 220 times the single RADFET sensitivity. This enables radiation sensitivities in the milli-rad range to be measured. Theoretical equations governing the threshold voltage of a MOS device as a function of bulk-source voltage are used to theoretically evaluate the output voltage of the stacked structure. Measurement and theory are found to agree closely in this analysis. % drift and % fading of the single RADFET, as a function of total radiation induced shift in V_T, is similar to that of the stacked structure.

I. Introduction

The use of pMOS devices (RADFET) to detect radiation was introduced by [1]. The concept of pMOS dosimetry involves measuring the change in threshold voltage resulting from a build-up of positive charge in the gate oxide of the MOS structure [2]. In order to increase the sensitivity of this device, different variables in the gate oxide growth cycle are optimised. RADFETs with gate oxide of thickness well in excess of 1μm are required to detect doses in the milli-rad range required for clinical/personnel applications. The long growth time involved prompted the investigation of a design approach to increase the radiation sensitivity of pMOS dosimeters [3]. In the design approach, separate devices were stacked such that n times the sensitivity of the single RADFET was obtained for n stacked RADFETs. In the work of [3], individually packaged RADFETs and thin oxide MOSFETs from a CMOS process were used to demonstate the concept. In the work described in this paper, the RADFETs were stacked on-chip and a single substrate technology is used. The single substrate technology is critical in the analysis of the stacked structure compared to that of [3]. In the current work it will be shown that stacking n RADFETs on-chip results in the stacked structure having a output voltage (Vo) much larger than n times the single RADFET Vo. Any change in the threshold voltage of the single device results in a much larger change in the stacked structure V_T. This effect is similar on the read-time drift, long-term fading and operating temperature characteristics of the stacked structure relative to the single device. It is shown in this work that single device radiation sensitivity as well as substrate doping concentration have the most important effect on the radiation sensitivity of the stacked RADFETs. This work shows theoretically that 40 stacked RADFETs should be capable of detecting doses in the low milli-rad range, which sensitivity could be required for low dose clinical/personnel applications. The possibility of scaling of RADFET sensitivity [3]; where a suitable number of RADFETs are connected using the stacked approach to obtain a required sensitivity, is also further investigated in this work. It is found that a straight line is obtained when the number of RADFETs is plotted against radiation sensitivity on a log/log scale. This is of particular interest for obtaining a dosimeter of a particular sensitivity.

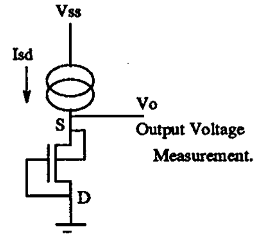

Fig. 1. Reader circuit for pMOS RADFET.

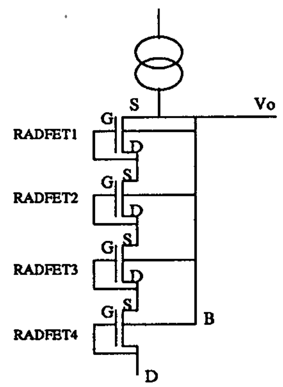

Fig. 2. Circuit schematic of 4 stacked RADFETs in the Reader Circuit, where S=Source, D=Drain, B=Bulk(substrate), G=Gate.

II. Theory

Using the approximate strong inversion model of [4], applied to pMOSFET; the following is the saturation current for the RADFET connected in the Reader circuit configuration shown in Fig 1, which is the usual dosimeter measurement set-up:

$$I_{SD} = \frac{\frac{W}{L}\mu C_{OX}[V_S - V_D + V_T]^2}{2(1+\delta)} \quad (1)$$

where W/L = Width/Length,
μ = Mobility,

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Cox = Oxide Capacitance/cm^2
$\delta = \frac{\gamma}{2\sqrt{-\phi_B - V_{SB}}}$
where $\gamma = \frac{\sqrt{2\epsilon q N_D}}{Cox} = SubstrateFactor$
where ϕ_B = Bulk-potential (-ve for pMOS),
N_D = Substrate doping.

The threshold voltage as a function of source-bulk voltage is:

$$V_T(V_{SB}) = V_{TO} - \gamma(\sqrt{-V_{SB} - \phi_B} - \sqrt{-\phi_B}) \quad (2)$$

where V_{SB} = Source-Bulk voltage,
V_{To} = zero bulk bias Threshold Voltage, linear mode intercept of I_{SD} versus V_{GS} for $V_{BS} = 0$V.

The design approach stacks RADFETs in series as shown in Fig 2. Applying these equations to the stacked structure connected as shown in Fig 2, the factors contributing to the output voltage of 4 stacked dosimeters is shown in Equation 3;

$$V_o = -4V_{To} + CURR3 + \gamma(\sqrt{-3V_{To} + CURR3 - \phi_B} - \sqrt{\phi_B}) + \sqrt{\frac{2I_{SD4}(1 + \frac{\gamma_4}{2\sqrt{-\phi_B - 3V_{To} + CURR3}})}{\frac{W_4}{L_4}\mu_4 C_{OX4}}} \quad (3)$$

$$CURR3 = CURR2 + \gamma(\sqrt{-2V_{To} + CURR2 - \phi_B} - \sqrt{\phi_B}) + \sqrt{\frac{2I_{SD3}(1 + \frac{\gamma_3}{2\sqrt{-\phi_B - 2V_{To} + CURR2}})}{\frac{W_3}{L_3}\mu_3 C_{OX3}}} \quad (4)$$

$$CURR2 = CURR1 + \gamma(\sqrt{-V_{To} + CURR1 - \phi_B} - \sqrt{\phi_B}) + \sqrt{\frac{2I_{SD2}(1 + \frac{\gamma_2}{2\sqrt{-\phi_B - V_{To} + CURR1}})}{\frac{W_2}{L_2}\mu_2 C_{OX2}}} \quad (5)$$

$$CURR1 = \sqrt{\frac{2I_{SD1}(1 + \delta_1)}{\frac{W_1}{L_1}\mu_1 C_{OX1}}} \quad (6)$$

assuming $\mu_1 = \mu_2 = \mu_3 = \mu_4$,
$W_1/L_1 = W_2/L_2 = W_3/L_3 = W_4/L_4$,
$C_{ox1} = C_{ox2} = C_{ox3} = C_{ox4}$.

Thus, it is seen that there is a superlinear dependence of the number of stacked RADFETs on stacked output voltage due to the increasing reverse bulk bias on increasing number device (increasing reverse bulk bias giving increasing V_T).

For 4 stacked RADFETs, the above equations give an output voltage of 29V based on a measured single device output voltage of 2.35V. This is very close to the measured value of output voltage for the 4 stacked RADFETs. Calculations show that the voltage across RADFET #4 (see Fig 2) in the reader circuit is approximately 15V (due to the high CURR3 value) [5], the voltage across #3 is 7.95, the voltage across #2 is 4.37 and across #1 is 1.75V. When exposed to 5krad(H_2O) accumulated radiation the single device output voltage Vo is changed to 3.9V. This resul in a calculated output voltage for the stacked structure of four RADFETs of approximately 40V, which is very clos to the measured value of V_T for this structure.

It is the term $\delta = \frac{\gamma}{2\sqrt{-\phi_B - V_{SB}}}$ for pMOS in Equatio 6 which is responsible for the amount of increase in th stacked structure output voltage compared to the singl device once the initial zero bulk bias threshold voltage c each device V_{To} is fixed. From this observation it may b seen that if the starting material is varied, the output voltage of the stacked devices with increasing device numbe may be controlled.

It may also be seen that the zero bulk bias output voltage of the individual device has the dominant effect on th stacked structure threshold voltage. This is seen in th single RADFET pre-irradiation Vo = 2.35V giving a Vo = 29V for 4 stacked RADFETs and for an accumulated dose of 5krad(H_2O) the single device Vo = 3.9V which makes the stacked structure Vo = 44V. Also, one can immediately see a potential draw-back in that 4 stacked devices give a pre-irradiation output voltage of close on 30V, which might not be practical from a power supply or measurement aspect. This substrate doping also precludes the use of more RADFETs stacked in series as the output voltage would exceed the reverse drain diode avalanche breakdown voltage ($\approx$ 75V) for more RADFETs in series, thus preventing the stacked structure from operating normally in this case. It is possible to choose a lower substrate material (i.e. lower N_D value in the equation for γ) such that the δ value is reduced, thus allowing more RADFETs in series, without reverse diode breakdown occurring, leading to higher radiation sensitivity. Lower δ results in less reverse bulk bias on increasing device number; i.e. lower body-effect factor.

In [3], because of a low reverse diode breakdown voltage, devices were stacked using separate chips, with each bulk connection tied to it's own source, and each drain connection tied to it's own gate. By this method of connection, the substrate bias of the device does not affect the threshold voltage and thus the total radiation induced shift in output voltage was simply the number of devices x radiation induced V_T shift of the single device.

III. Experimental Procedure

The reader circuit in Fig 1 is the measurement set-up used to measure output voltage Vo. When this set-up is applied to the stacked structure as shown in Fig 2, the external source and substrate are connected to the current source and the external drain is grounded. Samples were irradiated using Co60 γ irradiation at ESTEC with a dose rate of 50rad(H_2O)/min. Fig 2 shows the schematic of the stacked dosimeters and during irradiation the external drain (gate), source and bulk connections are grounded. The stacked RADFETs are connected such that each drain and gate of the individual device are connected and there is a common bulk connection to the source of the overall stack. A constant current of 10μA is applied and the output voltage for this applied current is a definition of

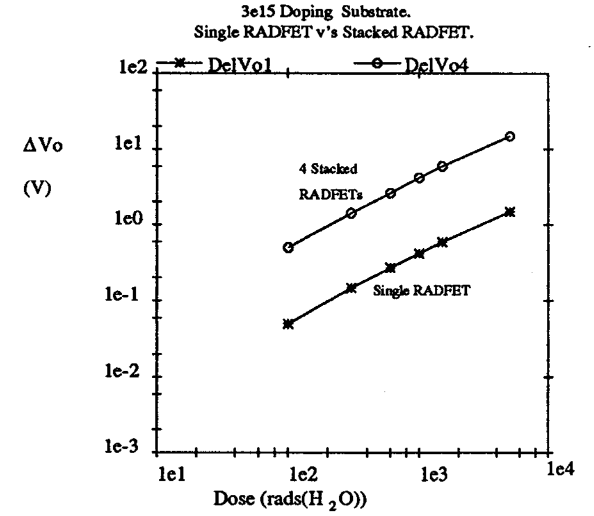

Fig. 3. Threshold Voltage Increase of a Single and Stack of 4 RADFETs with Dose.

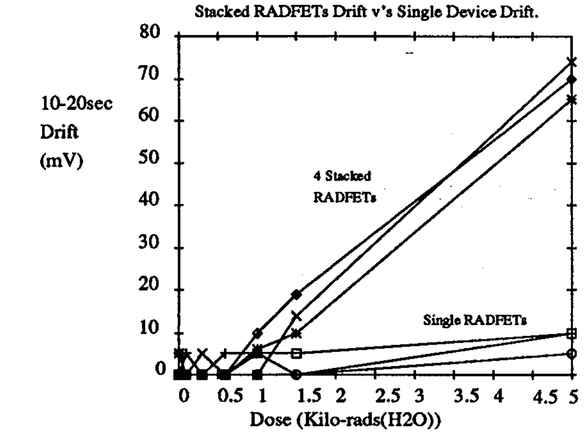

Fig. 4. Threshold Voltage 10-20sec. Drift of a Single and a Stack of 4 RADFETs as a function of Dose.

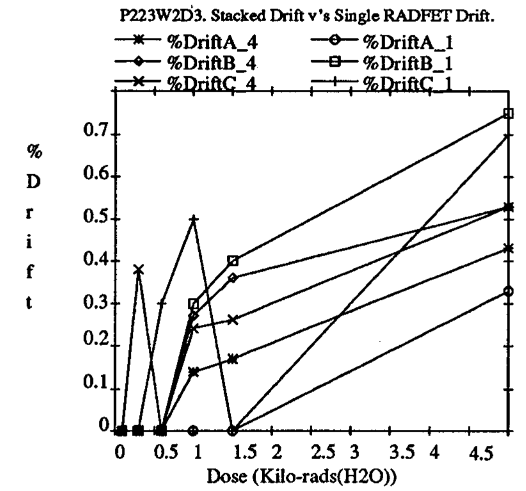

Fig. 5. Threshold Voltage 10-20sec. % Drift as a function of Threshold Voltage Radiation Induced Shift of a Single and Stack of 4 RADFETs with Dose.

threshold voltage, here termed Vo. Read-time drift after power-up is defined as the difference in Vo between 10 and 20second readings, using the Reader circuit configuration.

The technology used is the standard NMRC RADFET 0.4μm V_T adjust implanted (Boron implanted in to device channel in order to change V_T from -7V to arroximately 0V for 0.4μm thick gate) thermal gate oxide grown at 1000°C, metal gate process. Initial work was carried out using standard 3e15/cm^3 n-type wafers.

To examine the operating temperature dependence of the stacked RADFET structure, an ARTIC 60 temperature controller was utilised. A stack of 4 RADFETs was compared to the single RADFET's operating temperature dependence. Devices were biased in the reader circuit configuration with a constant 10μA current source. The output voltage at 10 seconds at different device temperatures is used to compare operating temperature dependence.

IV. Experimental Results

Fig 3 shows the output voltage increase with accumulated dose for a single RADFET and also a stack of 4 RADFETs in series. Fig 3 shows that the 4 stacked RADFETs gives approximately 10 times the sensitivity of the single RADFET.

From the presented theory, it would be expected that whatever drift is associated with RADFET 1 from Fig 2, (whose external pins are grounded during irradiation, essentially making this a single device), the effect on the stacked structure would be the same order of magnitude times greater as found from the sensitivity curves in Fig 3. A diagram of 10-20sec. drift after power-up of the circuit is presented in Fig 4. This diagram includes the results from 3 different devices. It may be seen that, allowing for measurement noise (5mV minimum resolution on HP Parameter Analyser), the drift for 4 stacked devices is 10 times the drift of the single device. Thus drift values of approximately 70mV are encountered for 4 stacked devices at an accumulated dose of 5krads(H_2O) compared to the approximate 7mV drift associated with the single RADFET at this dose. Looking at the % drift as a function of radiation induced shift in V_T in Fig 5, it may be seen that this value is less than 1% for the stacked configuration of 4 RADFETs, which is approximately the same as the single device, which is expected as the same order of magnitude increase in ΔVo and drift had been obtained. In Fig 5, it is seen that % drift increases with accumulated dose due to increased buildup of interface states.

Fig 6 looks at the long term stability of the single and stacked RADFETs, where the annealing of the shift in threshold voltage is examined as a function of time. Further evidence of the effect of reverse bulk bias is seen in this experiment where the amount of fading of the 4 stacked RADFETs is again 10 times greater than the fading of the single device. The % fading as a function of radiation induced shift in V_T of 4 stacked RADFETs fading would be expected to be of similar magnitude to the single RADFET fading, from previous discussion; this is the case, the value being 3.2% after 2400hours.

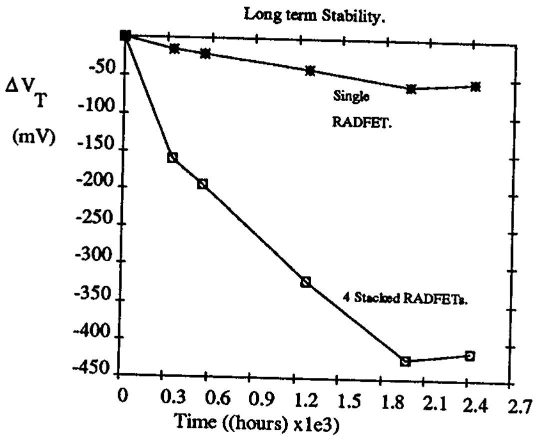

Fig. 6. Long Term V_T Fading of a Single and Stack of 4 RADFETs as a function of Post-Irradiation Time.

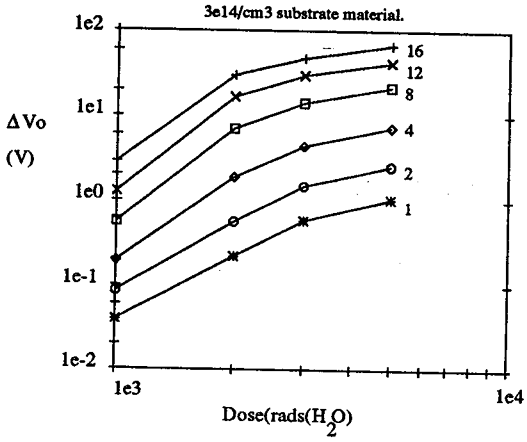

Fig. 7. Threshold voltage v's Dose for 3e14/cm3 substrate, V_T Adjust Implanted Stacked RADFETs. The change in δVo is shown for 1,2,4,8,12 and 16 stacked RADFETs.

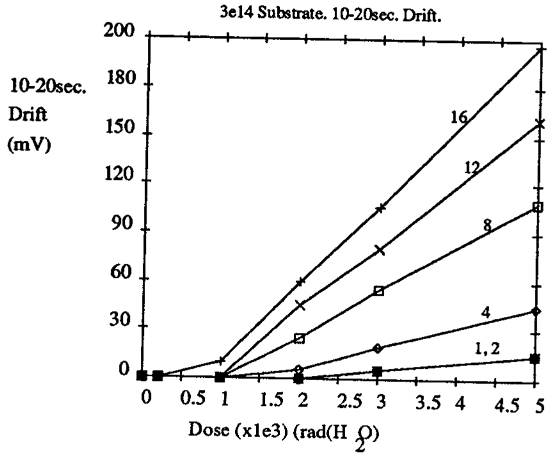

Fig. 8. 10-20sec. Drift of Stacked 3e14/cm3 substrate, Implanted RADFETs versus Dose. Drift curves are presented for 1,2,4,8,12 and 16 stacked RADFETs.

The TVTC or Threshold Voltage Temperature Characteristic ($\Delta Vo/^{o}C$) for 4 stacked RADFETs is approximately nine times the single device TVTC; the values being -38.5mV/°C and -4.3mV/°C respectively. This is approximately the same relation as obtained for the radiation characteristic of four stacked RADFETs compared to the single device, where 10μA was also used to measure radiation sensitivity.

As discussed previously, using a lower doping substrate should allow more RADFETs to be placed in series. Wafers were fabricated with a reduced doping substrate of 3e14/cm^3. The δ value for 3e15/cm^3 n type substrate is 2.065. The δ value for 3e14/cm^3 substrate is 0.709. Thus the "CURR" values from equations 3-6 are lower, resulting in a smaller build-up of threshold voltage for the stacked structure.

Despite using lower substrate doping wafers, it is possible to connect only 8 RADFETs using this stacked approach with un-implanted RADFETs. This is because of the high ($\approx$ -5.5V) initial threshold voltage of the single RADFET. It was thus decided to use a V_T adjust implant to obtain a threshold voltage of approximately 0V for the single device so that more RADFETs could be stacked in series. The implant used was 1.76e11/cm^3 at 120keV. This placed the single device V_T at +1.5V, i.e. in depletion mode.

For the reader circuit to be operational for pMOS; Vo > 0V, which requires $V_T < 1.375$V, from reader circuit output voltage equation. If V_T is above this value, then the drain-bulk diode turns on first and the reader circuit is no longer operational. On being irradiated, the threshold voltage shifts in the negative direction, and the reader circuit becomes operational at a particular accumulated dose.

Two different stacked RADFETs layouts were irradiated in ESTEC to examine the implanted lower substrate doping material, one layout with 16 RADFETs stacked as in Fig 2 and another with 40 stacked RADFETs as in Fig 2. Fig 7 shows the variation of threshold voltage with dose of 16 stacked devices. A table of radiation sensitivities for the 16 stacked RADFETs is shown in TABLE I.

For 2 - 8 stacked RADFETs, sensitivity values are for dose range of 2 to 3 krads. This is because a dose of marginally greater than 1krad was required to make the RADFETs enhancement mode devices. The 3-5krad radiation sensitivity values are lower than the 2-3krad values, due to the onset of saturation of ΔV_T.

Fig 8 shows the 10-20sec. drift of the implanted 3e14/cm3 substrate RADFET. Again, the ratio of drift of 16 stacked RADFETs compared to the single device is the same as the ratio of their radiation sensitivities. Looking at the %drift as a function of radiation induced shift in Fig 9, it is seen that the % drift as a function of total shift of V_T due to radiation does not increase as more devices are stacked in series. This is expected due to the increase in radiation sensitivity as well as 10-20second drift. The % drift of the single device in Fig 9 may be affected by measurement system noise.

40 stacked RADFETs were also designed as part of the layout in this work [5]. Fig 10 shows the radiation induced shift in V_T as a function of dose. TABLE I gives

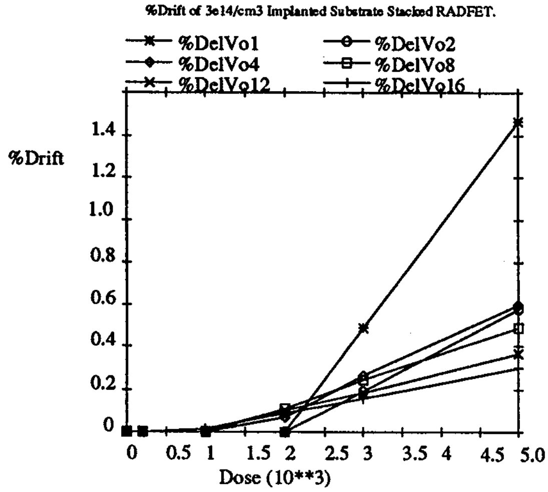

Fig. 9. 10-20sec. %Drift of Stacked 3e14/cm3 substrate, Implanted RADFETs as a Function of Total radiation Induced V_T Shift versus Dose. Included are values of 1,2,4,8,12 and 16 stacked RADFETs.

# RADFETs	Sensitivity (mV/rad(H_2O)
2	0.92 (2-3krad)
4	2.62 (2-3krad)
8	7.38 (2-3krad)
16	25.5 (1-2krad)
20	39.33 (1-2krad)
24	55.2 (1-2krad)
40	82.6 (200-1krad)

TABLE I

STACKED 3E14/CM3 SUBSTRATE, IMPLANTED RADFETS VERSUS RADIATION SENSITIVITY. DOSE AT WHICH SENSITIVITY IS EVALUATED IS SHOWN IN BRACKETS.

radiation sensitivity values for increasing number stacked RADFETs for different dose ranges up to 40 stacked RADFETs. The 200-1krad dose-range was used to evaluate the radiation sensitivity of 40 stacked RADFETs as saturation occurs very soon after 1krad accumulated dose for this number of RADFETs. The sensitivity achieved by 40 stacked RADFETs was 82mV/rad which is approximately 220 times the single device sensitvity. As seen from Fig 10, the radiation induced shift in V_T is of such magnitude for 32 and 40 stacked RADFETs that the reverse drain diode breakdown voltage of approximately 95V is reached at some dose between 1 and 2 krads(H_2O). Similarly for 24 stacked RADFETs, the reverse diode voltage is reached at some point between 2 and 3 krads(H_2O). This is another advantage in using the 3e14/cm^3 substrate material; that the reverse diode breakdown voltage is higher for the lower substrate material (compared to $\approx$ 75V for 3e15/cm^3 substrate), allowing more RADFETs to be stacked in this configuration to give greater dose measurement range prior to breakdown occurring.

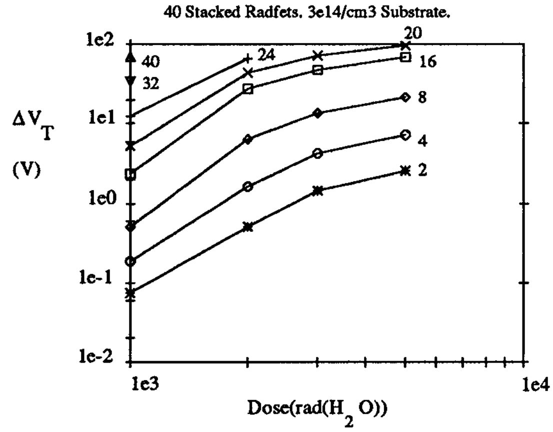

Fig. 10. Threshold voltage versus Dose for 40 3e14/cm3 substrate, V_T Adjust Implanted Stacked RADFETs.

V. Discussion

The capability to stack in series up to 40 RADFETs with a radiation sensitivity range of 0.36mV/rad(H_2O) to approximately 82mV/rad(H_2O) is the basis of what was originally termed by Kelleher [3] auto-scaling of RADFET sensitivity. By this idea, the required number (#) of stacked RADFETs are accessed to suit a particular radiation sensitivity requirement.

Fig 11 shows the number of RADFETs plotted against RADFET sensitivity, this is shown to give a straight line when plotted on a log/log scale. This curve may be used to calculate the number of RADFETs required for a particular sensitivity application.

In an attempt to evaluate the effect of using higher sensitivity RADFETs in the stacked structure; theoretical equations are used to calculate the radiation induced shift in

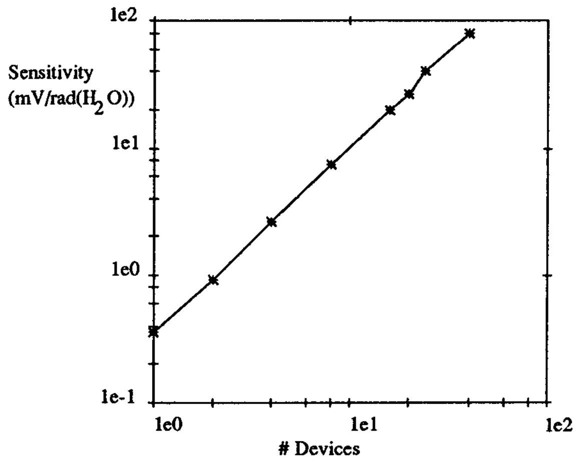

Fig. 11. Radiation Sensitivity versus Number of Stacked 3e14/cm3 Implanted RADFETs.Sensitivity calculated at 2krads.

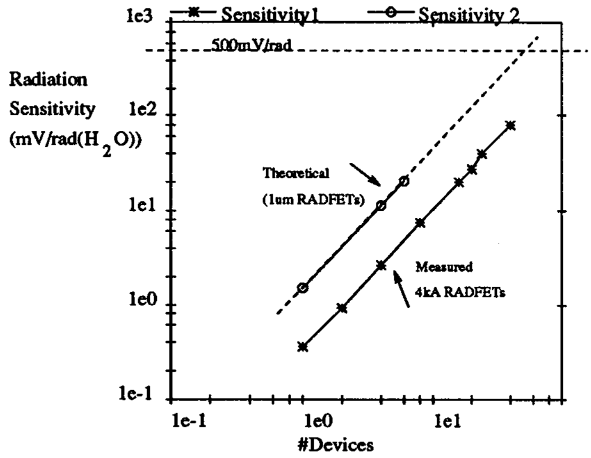

Fig. 12. Radiation Sensitivity versus Number of Stacked 3e14/cm3 Substrate RADFETs. Two RADFETs are used; the implanted 4k gate oxide already described, and the second is a theoretical curve evaluated for a $1\mu m$ implanted RADFET.

V_T of the stacked structure of $1\mu m$ implanted gate oxide RADFETs. The ΔV_T of an actual single $1\mu m$ gate oxide RADFET is measured. Fig 12 shows the radiation sensitivity versus number of RADFETs for the $0.4\mu m$ implanted RADFET and the theoretical curve which may be predicted using a $1\mu m$ gate oxide implanted RADFET. The theoretical curve in Fig 12 for all points except #Devices = 1 is thus theoretical. The 1.5mV/rad(H_2O) radiation sensitivity of the single $1\mu m$ gate oxide device is seen to increase with increasing device number with the same slope as the $0.4\mu m$ device. This is so because the calculations for the theoretical curve were calculated using the same substrate doping. It is thus possible to use fewer RADFETs to obtain the same radiation sensitivity, if the sensitivity of the single device is optimised. By this approach, it may be possible to obtain a radiation sensitivity in the mV/mrad range (based on a 20mV minimum allowable signal change [2]), required by low dose clinical/personnel applications. Fig 12 shows from the extrapolated dashed line that it should be possible to obtain a radiation sensitivity of 0.5mV/mrad(H_2O) (i.e. 500mV/rad(H_2O)) using approximately 40 $1\mu m$ gate oxide implanted RADFETs which have a single device sensitivity of 1.5mV/rad(H_2O). Assuming a minimum allowable signal shift of 20mV, then it would be possible to measure a minimum of 40mrad (H_2O). It should be possible by further process optimisation to obtain higher single device radiation sensitivity, in which case fewer RADFETs are required to detect milli-rad doses. The above discussion has dealt with 0V irradiation bias on all external pins only. It also possible to put positive bias on the gate of RADFETs in the stack, thereby increasing total radiation sensitivity. This should greatly enhance radiation sensitivity and achieve a radiation sensitivity that could measure doses in the low milli-rad range.

VI. Summary/Conclusions.

The possibility of stacking RADFETs with the purpose of improving radiation sensitivity has been investigated and found to have impressive possibilities. Responsivity to radiation is greatly enhanced and % drift as a function of radiation induced shift in V_T is not found to degrade with increasing number of stacked RADFETs. Also the long term relaxation of V_T is larger for stacked RADFETs but again, the %fading (i.e. as a function of radiation induced shift in V_T) is similar to the single device.

Stacked RADFETs were first fabricated using 3e15/cm3 doping substrate and the gate oxide V_T adjust implanted. The V_T of the single RADFET was -1V approximately. It was possible to stack only 4 RADFETs using this arrangement before the diode reverse breakdown voltage was reached. 40 RADFETs have been connected using the stacking approach. These RADFETs are fabricated on 3e14/cm3 substrate material, and the gate oxide V_T adjust implanted such that the threshold voltage of the single RADFET is close to zero. The lower substrate doping material enables more RADFETs to be connected by the stacking approach because of a lower substrate factor, hence the bulk bias effect on increasing number RADFET is less than in the case of a more highly doped substrate. This allows RADFET sensitivity in excess of 80mV/rad(H_2) for 40 stacked devices evaluated at a dose range of 2-3krad. This is 220 times the sensitivity of the single RADFET. It has been shown theoretically that radiation sensitivity in the mV/mrad range can be achieved by optimising the single device sensitivity. It is also possible to apply bias during irradiation to enhance the radiation sensitivity, in which case milli-rad doses could be detected more easily by fewer RADFETs.

References

[1] A. Holmes-Siedle, "The space charge dosimeter - general principles of a new method of radiation dosimetry,," *Nucl. Instrum. Methods*, vol. 121, p. 169, 1974.

[2] A. Holmes-Siedle and L. Adams, "Radfet - a review of the use of metal-oxide-silicon devices as integrating dosimeters," *Radiat. Phys. Chem.*, vol. 28, no. 2, pp. 235–244, 1986.

[3] A. Kelleher, W. Lane, and L. Adams, "A design solution to increasing the radiation sensitivity of PMOS dosimeters," *IEEE Trans. Nucl. Sci.*, vol. 42, no. 1, 1995.

[4] Y. P. Tsividis, *Operation and Modelling of the MOS transistor.* Mc. Graw Hill, 1987.

[5] B. O. Connell, "Increasing the radiation sensitivity of pMOS dosimeters." Masters Thesis submitted to National University of Ireland, 1995.