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THE USE OF RADFETS
IN RADIATION DOSE MEASUREMENT:
REPORT ON THREE LOTS PREPARED
FOR THE US ARMY:
FINAL TECHNICAL REPORT

by

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The final report describes the preparation of experimental RADFET dosimeters prepared by REM, a UK firm. Samples were delivered to the US Army for testing. The object was the evaluation of the Radiation - Sensitive Field Effect Transistor (RADFET) for use in tactical dosimetry systems. Three lots of the new Type TOT500 quadruple - transistor RADFET design were prepared and preliminary evaluations of each lot were made in the UK. A dose range of 5 to 5000 rads (0.05 to 50 Gy) is predicted. Special ceramic packages with a reduced amount of gold in the cavity were used. The "zero bias" mode, which eliminates batteries from tactical dosimeters, was proved to be useful. The prospects of the RADFET as a practical dosimeter look encouraging.

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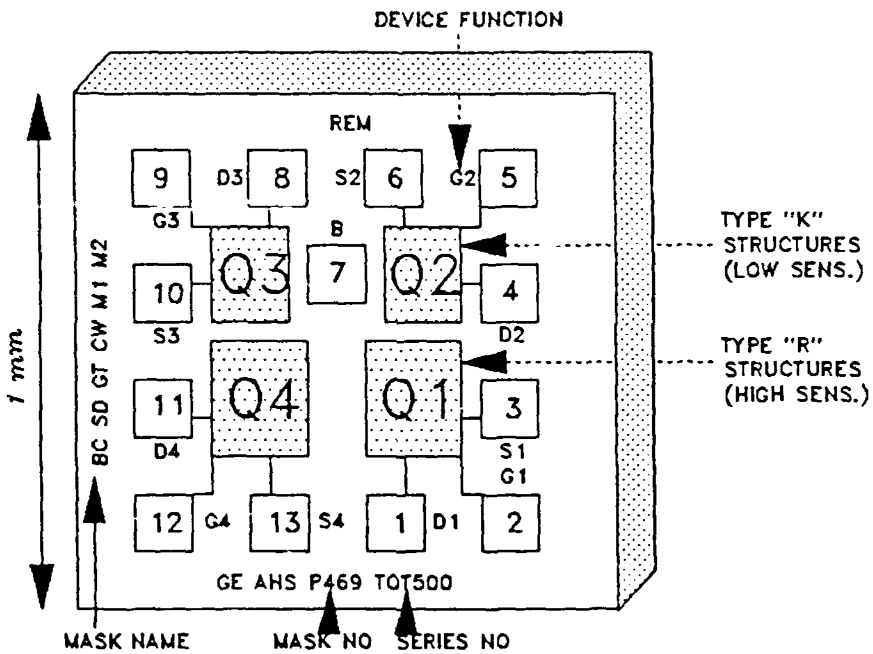

Outline Layout of TOT500
Quadruple RADFET Chip

FINAL REPORT

REM - FM - 89 - 2

THE USE OF RADFETS IN RADIATION DOSE MEASUREMENT: REPORT ON THREE LOTS PREPARED FOR THE US ARMY

ABSTRACT

Report No. REM-FM-89-2 is the final report on a series of experimental RADFET dosimeters prepared by REM, samples of which were delivered to the US Army for testing. The object of the project was the evaluation of the RADFET principle for use in tactical dosimetry systems. REM, a UK firm, delivered three lots of the new Type TOT500 quadruple - transistor RADFET design and made preliminary evaluations of each lot in the UK. This report surveys the preparation of three RADFET lots, wafer probing, packaging and the measurement of response to gamma rays. A performance range of 5 to 5000 rads (0.05 to 50 Gy) is predicted. A new design of bench test circuit for RADFETS was [illegible] Special ceramic packages with a reduced amount of gold in the cavity were used for several batches and these have proved superior to conventional ceramic packages as regards low - energy X-ray response. In the above program, REM was able to confirm the suitability of the "zero bias" mode, which eliminates batteries from tactical dosimeters. Overall prospects of the RADFET as a practical dosimeter look encouraging and a proposed program of further work is outlined.

LIST OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

THE USE OF RADFETS IN RADIATION DOSE MEASUREMENT: REPORT ON THREE LOTS PREPARED FOR THE US ARMY

FINAL TECHNICAL REPORT

1. Introduction

REM, a UK firm, has completed a contract to supply to the US Army several batches of silicon MOS RADFET dosimeters. This document is the final report on that contract. RADFETs (Radiation - Sensitive Field Effect Transistors), are based on p-channel Metal - Oxide - Silicon (MOS) technology. The concept has been in development by REM and others since REM described the concept in 1974. The devices supplied in this contract were fabricated to REM's design under subcontract by the Industrial Liaison Unit of Southampton University Microelectronics Centre, England.

The TOT500 quadruple - transistor design has been developed over the past five years. The contract with the US Army called for delivery of samples from three different process runs, with the object of demonstrating the degree of reproducibility which could be obtained. The ownership of the process batches lies with REM and an agreed number of samples have been released to the US Army.

The first batch, TOT501A, was fabricated on 3-inch silicon wafers in 1987. This was the first batch produced with the new TOT500 mask design. The results were remarkably successful, giving radiation responses as predicted, high yield, low threshold voltages and low drift. The second batch, TOT501B, was fabricated in late 1988 on 4-inch wafers; devices had better stability and similar radiation responses as expected . The third batch, TOT501C was fabricated in the Spring of 1989, confirmed the question of repeatability. Minor process improvements were attempted with the second and third batch, some of which proved useful. Each process lot was subjected to trials by the author before suitable wafers were selected and a production lot was packaged for the US Army.

This report summarises the work performed by REM, including wafer probing, packaging, the improvement of measurement methods and the analysis of RADFET response to gamma rays. The report concludes with a proposal for further work, including some original ideas for advanced RADFET structures and a task which ensures that measurements by REM and the US Army will be co-ordinated in future work.

2. DESCRIPTION OF PROCESS LOTS TOT501A, B AND C

2.1. Introduction and Description Of RADFET Device

The RADFET is an integrating dosimeter. Dose is determined by the measurement of long-lived trapped charge, generated by radiation in the grown silicon dioxide layer on silicon. The principle was first described in detail by Holmes-Siedle in 1974 and a full description is to be found in a review by Holmes-Siedle and Adams, written in 1986.

An MOS transistor, when exposed to radiation, exhibits a shift in its current-voltage characteristics due to the long-lived charge produced in the insulator layer, normally silicon dioxide, by the removal of electrons and the trapping of holes. The threshold voltage of a p-channel MOS transistor device shifts to a higher value and it is possible to track this voltage value and infer the absorbed dose from the observed shift, using a calibration curve. The measurement is best made using a reader, which can be described as a "V(T) Tracker". REM has collaborated with SILTECH, a UK firm in the development of a reader designed especially to address the four RADFETs on the TOT500 chip.

2.2 Description of the TOT500 RADFET Chip

The RADFETs developed by REM are based on metal-gate p-channel MOS technology. They differ from pMOS logic devices in that they contain very thick gate oxides and very thin aluminium gates. The TOT500 contains two matched pairs of pMOS RADFETs. Details of the physical layout are shown in Figure 1.

In the TOT500, one pair of pMOS FETs is of Type "R", which carries a THICK gate insulator. This makes it extra sensitive to radiation. The thickness is about ten times normal thickness. This yields a dosimeter suitable for low doses ("R" stands for "rad" doses). The other pair, Type "K", carries an oxide which is relatively THIN but still several times thicker than normal. The Type K RADFET is suitable for moderate to high doses ("K" stands for "kilorad" doses). The circuit symbol and the pin arrangement of the quadruple device are shown in Fig. 2. It can be seen that the four devices can be operated as separate sensors or can be cascaded to provide enhanced response or compensation for one another.

The dimensions of the TOT500 die are only 1.0 x 1.0 mm, which make single chips suitable for very small diameter medical probes and allow several dies to be mounted as a multiple array in a small space. These general concepts are shown in Fig.3.

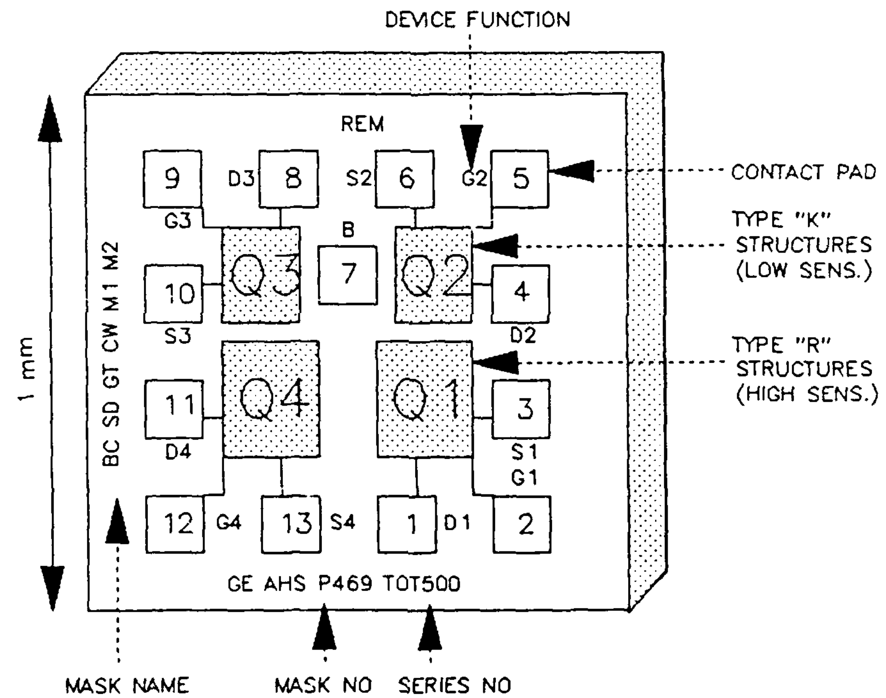

Fig. 1 Outline Layout of TOT500
Quadruple RADFET Chip

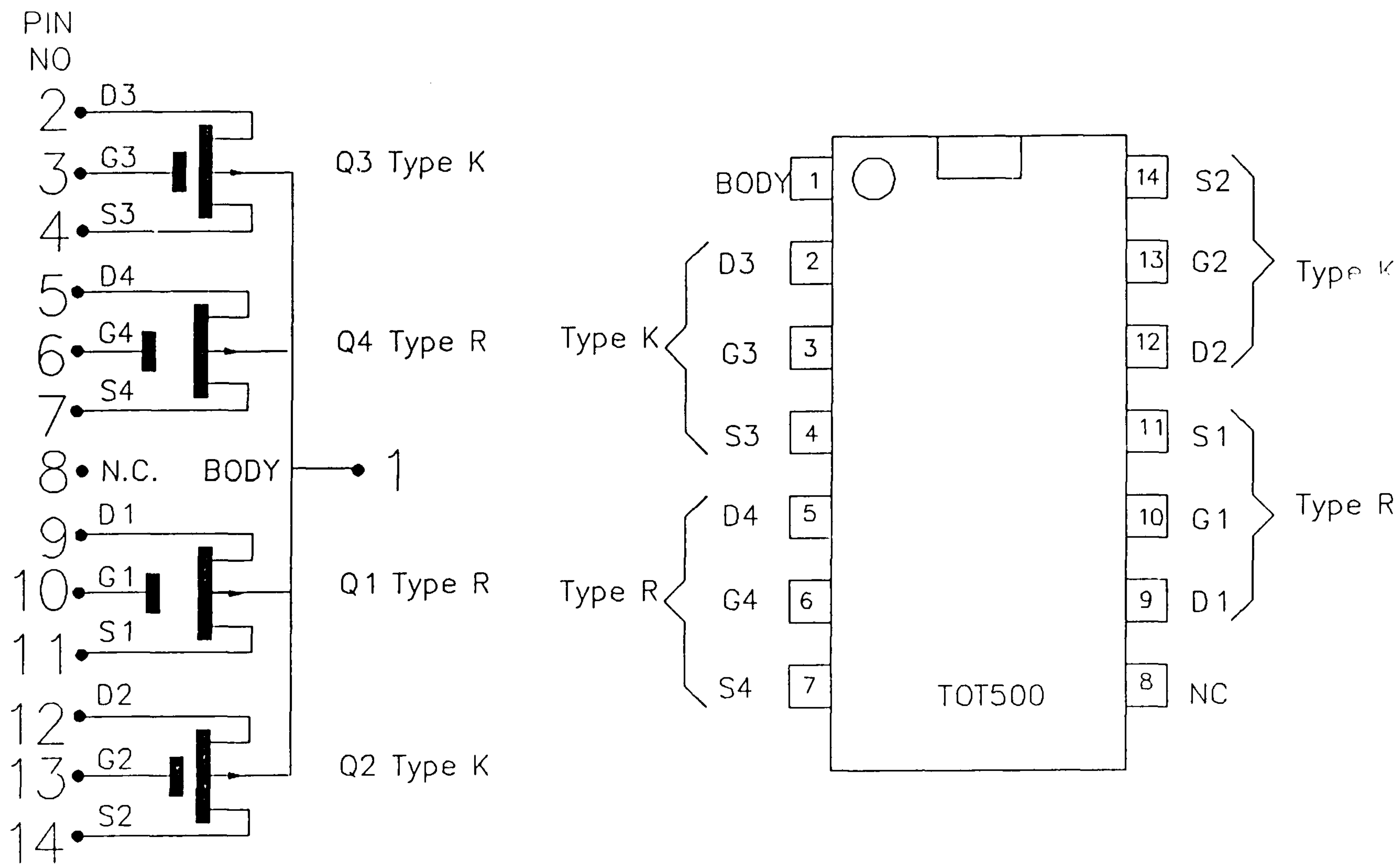

Fig 2 :14–Pin DIL form of the TOT500
RADFET: pinout diagrams

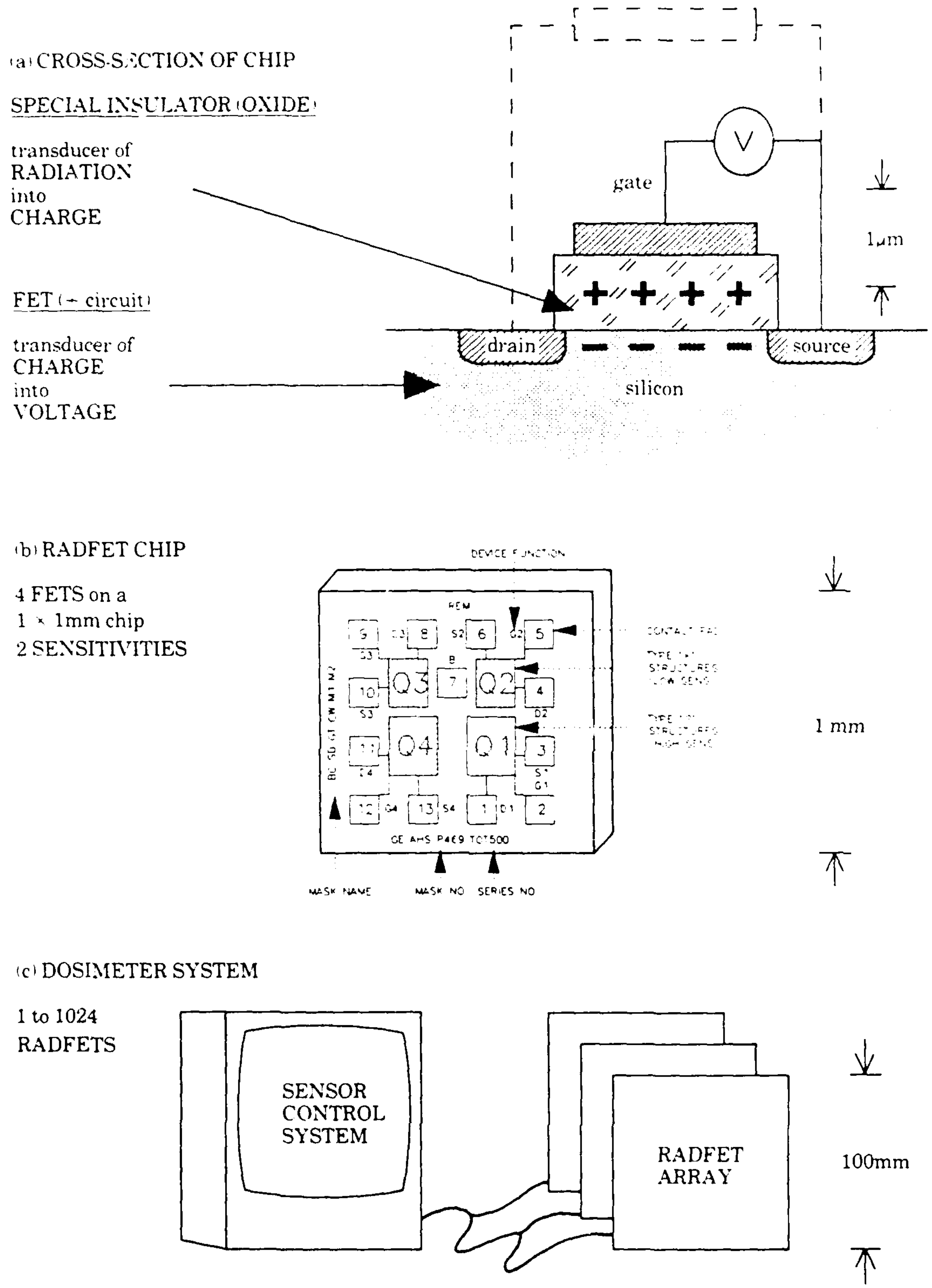

Fig.3. Principle of a dosimetry system based on the RADFET (RADiation-sensitive Field Effect Transistor).
(a) microscopic cross-section of chip
(b) chip layout (c) dosimeter system

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The use of thin aluminium gates serves two functions. The gate layer provides less scattering to low - energy radiation than the normal MOS transistor; also, it is possible to admit ultraviolet light, which can serve to annihilate the trapped positive charge and hence "erase" the dosimeter signal.

2.3 Silicon Wafer Fabrication Runs

The first fabrication run of the new TOT500 RADFET was made in December 1987. The run was called TOT501A (i.e. run "A" of recipe 501). Twelve 3 - inch wafers were started and 11 came through. The second run, TOT501B, was performed in late 1988. Six 4-inch wafers were processed using two different oxidation techniques. Only one process gave the desired low V(T) values. The third run, TOT501C, was performed in Spring 1988. All six wafers were functional. A summary of their properties is given in Table 1.

The procedure for wafer probing and sawing was as follows. The wafer was divided into about ninety 8 x 12mm regions with a block number assigned. Each "block" contains 96 RADFET dies. The map diagram is shown in Figure 4.

The block numbers were used as a map reference when taking samples of dosimeters from various parts of a wafer. Instructions based on this mapping system were given to our subcontractor, MTL of Alton, Hampshire, England for sawing and packaging of single chips.

2.4 Packaging

For the US Army evaluation, a commercial 14-pin dual-in-line package was used. This gave contact to all four RADFETs and much of the surroundings were of low atomic weight i.e. ceramic, except for the kovar pins brazed onto the sides and the gold-ceramic inks used for the screen printed leads and ground plane under the chip. The wiring was ultrasonic wedge bonded aluminium wire. The chip was bonded to the substrate with polyimide resin. A ceramic lid was sealed on with epoxy adhesive, giving a low atomic weight (low-Z) covering and a low sealing temperature.

Dr. Stanley Kronenberg has found that low - energy X-ray response is strongly affected by the amount of gold inside the encapsulation of the device. If gold surfaces are exposed to low - energy photons, then photoelectrons are emitted. Given the correct geometry, these can strike the MOS chip and give an over - response.

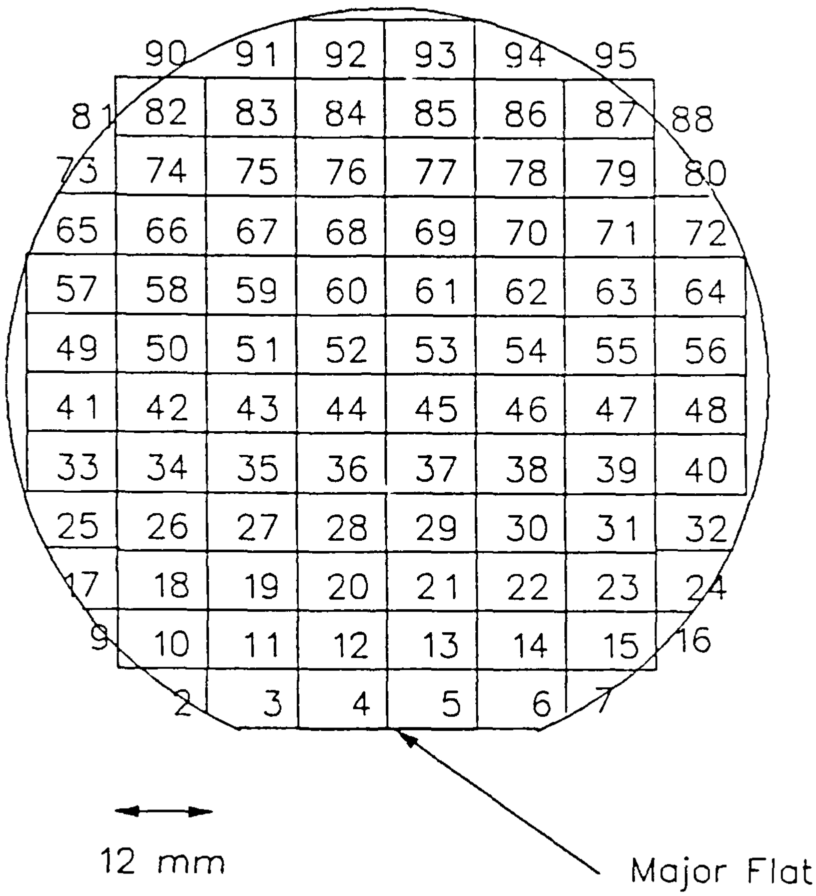

Fig. 4 Wafer map reference system for 100mm (4 inch)
Wafer divided into 8x12 blocks of 1mm squares

A task was added to the contract to address this problem by preparing some devices with standard gold content and others with low gold content. In response to this task, REM commissioned a special "low - gold" (abbr. "LG") package from the suppliers of the standard ceramic DIL package (abbr. "STD"). By an alteration in the tooling, as much gold as possible was eliminated.

Initial tests on the "LG" devices showed no unusual responses under gamma irradiation and good electrical performance. Thus, although these special packages had a higher unit cost, REM adopted this package type for the majority of the devices delivered from lot 501B and 501C. A small number of "extra" devices was delivered in the standard (high gold) package so that the US Army could carry out the desired experiments on gold content. The latest report is that the LG packages performed well under low - energy X-rays.

2.5 Trials Procedure

In all runs, MTL divided certain wafers into two halves and diced the left-hand half using a wafer saw. Blocks selected by REM based on the wafer probe data were mounted in the ceramic DIL packages. The trial samples were carefully evaluated for radiation response and electrical properties by REM. Lots had numbers such as :

TOT501B - 4 - 1

(i.e. packaging lot 1 from wafer 4 of run 501B using mask TOT500)

2.6 Production Lots

On the basis of these trials, a larger production lot was ordered. For runs 501B and C, most of the samples came from one favoured wafer, so as to provide the US Army with a uniform batch for distribution.

The number to be delivered was 140 plus some specials. The number ordered from MTL was thus set at a level which allowed for some loss due to bonding failures or poor electrical performance. Chips in non - gold packages constituted the majority. To facilitate controlled experiments on the effect of gold and of wafer variation, small numbers of other combinations were also ordered. The results of the performance measurements are given in Sections 3 and 4 of this report. Some highlights of those results are given in Table 1.

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TABLE 1 SUMMARY OF THE ELECTRICAL AND DOSIMETRIC PROPERTIES OF THE FIRST THREE PROCESS LOTS OF THE TOT500 RADFET

REM LOT NO.			501A	501B	501C
WAFER LOT			P133U	P342U	P417X
RUN DATE			12/87	12/88	6/89
WAFER SIZE			3"	4"	4"
OXIDE THICKNESS					
RADFET type R (um)			0.82	0.83	0.86
RADFET TYPE K (um)			0.25	0.25	0.26
THRESHOLD VOLTAGES					
Vt ; R	(V)	typ.	7.3	6.1	6.1
Vt ; K	(V)	typ.	3.7	3.4	2.7
GAMMA RAY RESPONSIVITY					
r(+) ; R	(mV/rad)	typ.	2.8	9.0	9.9
r(+) ; K	(mV/rad)	typ.	0.30	1.6	0.60
r(0) ; R	(mV/rad)	typ.	1.1	0.9	1.1
r(0) ; K	(mV/rad)	typ.	0.20	0.20	0.20
STABILITY					
du (10s)	(mV)	typ.	3	2	1

V(T) = threshold voltage 10uA ; r(+) = radiation response with +20V on gate ; r(0) = response with all leads shorted; du = drift up i.e. difference of V(T) at t=5 and 10 seconds after switching to "read" mode.

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3. MEASUREMENT PROCEDURES AND RESULTS

3.1 Measurement Procedures

3.1.1 Electrical

The dosimetric measurement made on a RADFET is an electrical measurement of the "threshold voltage", which in this case is actually the voltage of a point on the I(D) vs. V(G) curve at which a given value of I(D) is drawn. This value is usually 10, 40 or 100 microamps (hereafter abbreviated to uA). The "Readers" used for dosimetry are simple "V(T) Trackers" which set this current automatically and read out the voltage drop to millivolt accuracy. In the present project, the electrical measurements made on RADFETs in their mounted state included:

A. BEFORE SELECTION FOR AN EXPERIMENT

(a) Curve Tracer Check
1. I(D) vs. V(DS) curve
2. I(D) vs. V(G) curve

(b) Check of Gate Leakage I(G) under +5 and possibly -5V

(c) VT Tracker measurement of :

```
    V(T) at 10 microamps                )
    V(T) at 40 microamps                )....before and after
                                        )        + stress
   drift of V(T) at 10 and 20 sec       )     (e.g. V(G) = +20V)
```

B. BETWEEN IRRADIATIONS

(c) VT Reader measurement of :

```
    V(T) at 10 microamps    )
    V(T) at 40 microamps    )...............as dictated by the
    drift of V(T)           )                  experiment.
```

A pair of measurements, say at 10 and 40 uA, may be called a "Health Check", because the difference between the two V(T) measurements, usually about 300 mV, is a useful rapid check of the I-V characteristic of the device and the transconductance value (di/dv = 3 x 1E6 / 0.3 = 30 umho). If the device has failed and is acting purely as a passive load in the circuit, it is unlikely to produce this same value correctly. The other main "health" criteria are the integrity of the gate oxide and the stability of V(T) values when the oxide is exposed to applied fields in the "read" and "stress" modes.

3.1.2 New V(T) Tracker Design

Using lessons learnt in the earlier measurement campaigns, a V(T) reader was developed to make manual measurements as quick and accurate as possible. A prototype version of this reader was designed by SILTEC based on REM'S specifications and ergonomic design. A production model of this tracker, the RDR100 reader, was supplied to the US Army for RADFET evaluation work.

The RDR100 can apply three conditions to each of the TOT500 elements, namely:

"READ" (a low negative voltage on the gate, equal to V(T))

"EXPOSE" (a chosen stress voltage between gate and body)

"SHORT" (body, source, drain and gate shorted together)

The tracker allows quick access to each of these devices in turn. The power supply allows "headroom" for large excursions of threshold voltage. The RDR100 is not a Dosimeter, since it does not convert the voltage changes to to doses. Further development is needed for a dosimeter system.

3.2 Selection Criteria for Packaged devices

The normal criterion for threshold voltage stability is that the tracker display of V(T) does not change by more than 3 mV when read at 5 and then 10 seconds after switchon. The response of the wafers to positive bias stress was very uniform.

The accept/reject criteria used for the delivery lots are similar to those used by REM in earlier work, with developments to meet the quadruple design and the thicker oxide. The symbols used for the four-transistor chip as a whole include "Acceptable (A)", "Acceptable with only three devices working (A')" and "Rejected (R)". Further symbols are used, as shown in Table 2.

3.3.. Threshold Voltage at Wafer Probe Stage

The wafer runs were numbered TOT501A, B and C by REM. The wafer run numbers used by SUMC were P331U, P342U and P417X respectively. We will here use the simplified forms "501A" etc.

Table 2 . Grades of Dosimeter: Test Symbols

ACCEPTED	S	super stability
	Aeb	excellent (incl. bias use)
	Ae	excellent
	Agb	good (incl.bias use)
	Ag	good
	Af	fair
	Ah	high V_T
	Al	low V_T
WORKING BUT REJECTED	Rdd1, Rdd2	drift down: 1:small; 2:large
	Rdu1, Rdu2	drift up: 1:small, 2:large
	Ru	unsteady V_T value
	Rb	breakdown voltage low
FAILED	1.	Working Incorrectly
	Fpl	poor, leaky (e.g. V_{off} not flat vs. V_{DS}; gate leak to channel)
	Fpb	poor, breakdown early
	Fpo	poor (other characteristics poor)
	2.	Completely Failed
	Fsc	short-circuit, source to drain
	Foc	open-circuit, source to drain
	Fng	no gate control

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The threshold voltages of devices on wafers were measured using the Suss automatic prober at Southampton. Threshold voltage values for the thick oxides (0.8 micrometres) were lower in 501B and C than in 501A showing that less fixed oxide charge was being incorporated in the two later batches. Local scatter was also less, so that the mismatch between one transistor and its partner on the same die was less. Data on these trends are given in Table 3. This shows that the lowest mismatches for the 501C oxide were 2 mV, while the lowest for the earlier batches had been 40 Mv and 4 mV for A and B respectively. However, there is an unsatisfactory number of dies in all lots having mismatch values in the region of 50 mV. This is a significant value if two RADFETS are used in the differential mode. However, close matches can be selected manually. For zero-bias exposures(1 mV = 1 rad), a mismatch of 10 millivolts would appear as an initial reading of 10 rads on a differential V(T) tracker.

SUMC believes that the scatter in threshold voltages shown in recent batches cannot be reduced by any large amount. The scatter is probably the statistical spread in fixed oxide charge found naturally in thermally grown oxides or the spread of resistivity in the silicon. However, some of the RADFETS made for DREO (oxide thickness 0.5 um) have a much smaller spread at the wafer probe stage. Of 2,000 devices probed, less than 1 percent of the pairs deviated by more than 40mV and about 50 percent were within 5 mV. There is thus room for improvement in the present process.

3.4 Selection of Wafers for Trials

The wafer probe data were used to select wafers for the Trials Group, on which more detailed evaluation of properties in the packaged state, including response to stress and irradiation, were to be carried out. Three wafers are normally selected.

The criteria for a good dosimeter include the following initial electrical properties :

- low V(T) value
- small spread of V(T)
- good match between the two V(T) values on the same chip
- high stability of V(T)
- high yield in packaged form

TABLE 3. RESULTS OF WAFER PROBE TESTS ON RADFET WAFERS

Run No.	Wafer No.	TYP. VALUES & SPREAD OF V(T) Type R Dev. (mV)	TYP. VALUES & SPREAD OF V(T) Type K Dev. (mV)	WORST MISMATCH Type R Dev. (mV)	WORST MISMATCH Type K Dev. (mV)	AVERAGE MISMATCH Type R Dev. (mV)	AVERAGE MISMATCH Type K Dev. (mV)	BEST MISMATCH Type R Dev. (mV)	BEST MISMATCH Type K Dev. (mV)	YIELD (%)
501A	5	6.8 110	3.6 500	510	200	100	50	40	10	99
501B (R)										
	4	6.3V 350	3.4V 150	70	40	40	20	4	1	99
	5	6.3V 600	3.5V 20	180	110	50	50	6	4	99
	6	6.3V 900	3.3V 250	490	200	50	30	6	4	99
501B (E)										
	3	9.3V 2000	7.8V 800	1100	600	150	100	4	4	99
501C										
	2	6.3V 800	2.70V 300	700	120	50	30	2	2	99
	4	6.8V 650	2.65V 180	500	150	50	30	2	3	99
	6	7.9V 600	2.90V 180	500	150	80	50	2	1	99
	9	5.7V 900	2.50V 350	400	150	100	50	40	5	99

The first four criteria are obtained from the wafer map data and the yield at wafer probe gives some guidance as to the fifth criterion.

An example of the use of the probe data for selection of 501C devices is given below. Based on an initial wafer survey, Nos. 2,4,6 and 9 were selected for more extensive mapping. About 400 devices in the central region were probed and the results tabulated. Table 3 shows the spreads and other data from the devices in an 8 x 12 block.

Wafer 6 was eliminated from the trial group because of the consistently high values of V(T) in types R and K. Wafer 9 was included automatically because, in this wafer, one stage of heat treatment was intentionally omitted. The V(T) value obtained was the lowest so far for these oxide thicknesses and the responsivity values were thus of interest.

A comparison between wafers 2 and 4 showed that 4 was superior with respect to the spread of V(T) (650 vs. 800 mV for R and 180 vs. 300 for K) and the worst mismatches observed in R (500 vs. 700 mV). Other initial properties were about the same. Eventually 2 was the wafer chosen for the production lot, because it showed greater stability and repeatability of radiation response. The designation of the production lot was TOT501C-2-2.

3.5 Electrical Selection Tests on Packaged Devices

A log of measurements on a representative sample of the delivered devices was made and sent to the US Army along with the devices. Some data are included in Table 4 and are discussed below.

3.6 Objective of Electrical Tests

The objectives of the electrical tests were:

(a) to collect statistics on yield and spread of electrical properties;

(b) to select 140 "good" devices for the US Army from each run.

For the first production lot, manual measurement of a large sample and rejection of items with poor properties was thought to be the best approach for the project. This helped in the formulation of future runs and in finding the optimum instrumental setup with which to read RADFETs as dosimeters. However, for 501B and C, about 50 percent were measured and the reject rate calculated. Samples were then added to the total number delivered to allow for this rate.

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TABLE 4. THRESHOLD VOLTAGE, RESPONSIVITY AND STABILITY VALUES FOUND IN THE FIRST THREE PROCESS LOTS OF THE TOT500 RADFET

LOT NO.			501A	501B	501C
V(T) - R	(V)	max.	8.1	6.9	7.0
		min.	7.3	6.1	6.1
V(T) - K	(V)	max.	4.1	3.6	3.2
		min.	3.7	3.4	2.7
r(+) - R	(mV/rad)	max.	4.0	9.9	10.0
		min.	2.8	9.0	9.9
r(+) - K	(mV/rad)	max.	0.40	1.8	0.61
		min.	0.30	1.6	0.60
r(f) - R	(mV/rad)	max.	4.2	-	1.4
		min.	3.2	-	1.3
r(f) - K	(mV/rad)	max.	0.41	-	0.17
		min.	0.25	-	0.15
r(0) - R	(mV/rad)	max.	1.5	0.9	1.3
		min.	1.1	0.7	1.1
r(0) - K	(mV/rad)	max.	0.20	0.25	0.18
		min.	0.16	0.19	0.16
du (10s)	(mV)	max.	10	3	2
		min.	1	1	0
str(+18)	(mV)	max.	15	4	3
(10s)		min.	6	2	0
rlx(30s)	(mV)	max.	15	2	2
		min.	5	0	0

V(T) = threshold voltage 10uA ; r(+) = radiation response with +18V on gate ; r(f) = response with gate floating ; r(0) = response with all leads shorted ;
du = drift up of V(T) 10 seconds after switching to read mode ;
str = shift of V(T) after 10 sec. exposure to +20V on gate;
rlx = relaxation 30 seconds after above gate bias removed

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3.7 Yields

The yield of "good" devices at wafer level was over 99 percent. However, after packaging, gate to body shorts and other defects were found in the samples at a significant rate. For example in lot 501B, out of the first 107 devices measured, only 83 were found acceptable and 23 were rejected (about 20 percent reject rate). One "failure" mode - the "Unsteady V(T)" effect - was later shown to be caused by a specific feature of the V(T) tracker circuit used. This effect was eliminated by a redesign of the read circuit and (after delivery), a good number of the devices "rejected" were shown to have stable V(T) and act normally as dosimeters. Reject rates with the new circuit were now only about 10 percent.

The remaining rejects typically had "dead short" in one or two of the four devices, probably due to a local defect in the silicon. A few rejects were "open circuit", probably due to breaks in wiring or metallisation.

Reactions of the RADFETs to gate oxide stress (see "str ; rlx" in Table 4) show that the oxide in runs B and C were cleaner than in A, because they exhibited less ionic drift under a positive gate voltage.

3.8 Unwanted Electrical Effects

3.8.1 "Unsteady V(T)" Effect

In the V(T) tracker, the "V(T)" signal is the DC voltage of a node connecting the positive constant current supply with the source and body of the RADFET. The RADFET channel is an active load but any passive load put in the place of the RADFET yields a signal at this output node (at 10uA, a 100 kohm resistor yields 1V). Thus, "spurious V(T)" readings can be generated by a failed RADFET, which is presnting a passive load. If the load or the current fluctuates, then an "unsteady V(T)" is observed at the output node.

To buffer the node against current drain, the node is made the input to a unity - gain buffer amplifier. The tracker displays the amplifier output , suitably divided down. The "unsteady V(T)" observed can thus also be due to instabilities in the amplifier network. One special case of active generation of an unsteady V(T) signal is if the body of the RADFET is left floating.

On previous (single - channel) V(T) tracker circuits, minor unsteadiness of the V(T) signal was observed occasionally and the device rejected if this unsteadiness was more than 2 millivolts . However, in the prototype design of the RDR100 V(T) tracker, certain devices exhibited a large unsteadiness, which was not seen when the same device was tested on the previously used circuits. The devices concerned were also shown to be good active pMOS transistors when tested by curve tracer (I(D) vs V(DS) or V(G)). The effect was a puzzling one which held up delivery of lot 501B for some time. For safety, all samples which exhibited this condition were rejected from Delivery 0001AC, even though it was shown that the "rejects" would in fact act as dosimeters using simpler V(T) trackers.

Several changes were then made in the tracker, including modification of the power supply and buffer amplifiers. The effect still occurred when the power supply voltage was brought down to 12V in line with the ESTEC tracker box used for comparison. It was then realised that one significant difference in the new tracker box was that, when not being measured, all electrodes were grounded except the body and the source of the device being read. This placed a reverse bias across all of the "non-read" RADFETs. The final conclusion was in some TOT500 dies, there is leakage in these "non-read" source and drain diodes. This could pull down the potential of the output node until it dominated the signal. A modification of the circuit to short to the body all electrodes not being read eliminated the effect. The production version of the RDR100 contains this modification.

3.8.2 Short Channel Effects

We noted that the I(DS) - V(DS) characteristics of the TOT501A and 501B devices had a large slope on the saturation region of this characteristic. In non - VLSI transistors, this region of the I - V curve is normally nearly parallel to the V axis. SUMC's analysis of these curves suggested that this was consistent with a short channel, such as might be introduced by extra long heat treatment, as required by the growth of extra thick dosimetric oxide films. A channel length of 4 micrometres was calculated from the electrical characteristics of the devices, whereas we had planned for 8 to 10 micrometres after diffusion.

Our measurements indicated that this short-channel effect had no major drawback with respect to dosimetry action (which is present in 1.5 um VLSI) but led us to reduce heat treatment where possible in the last run, 501C.

3.9 Discussion of Electrical Measurements

Table 4 gives a summary of the key properties of the three process runs. Firstly, the numerical value of the threshold voltage, V(T), has fallen from Lot A to C, even though the oxide thickness has each time been slightly increased. This is probably due to improved cleanliness and timing control in the new 4-inch tube furnaces installed at SUMC. V(T) values of type R devices are the same for B and C. The same factors probably explain the much lower interface-state induced drift (du) and ion induced drift (str) in B and C.

The net result of the measurement campaigns on lots 501A,B &C has been a better knowledge of the problems and possibilities of the TOT500 RADFET design and quick procedures for scientific evaluation. The experience has also provided information for the design of tactical dosimetry circuits for multiple RADFET chips. We have determined that neither the "Unsteady V(T)" or the "Short Channel" effects have any serious impact on the use of the RADFET as a dosimetric device. The stability and uniformity of the product have improved over the relatively few process runs made.

4. Response to Gamma Rays

4.1 Summary

The RADFETs were exposed in the Fulmer Research Ltd. cobalt-60 cell at a dose rate of about 3 rad(Si)/sec. The time for a 100-rad exposure was about 36 seconds. The irradiation routine has been described earlier. The RDR100 reader reduced operator errors in applying bias and also made the readout operation many times quicker. In all cases, dose is expressed in rad(Si) (0.01 Gy(Si)) and the radiation is Cobalt - 60 gamma rays. Buildup material was placed between the chip and the source, usually the equivalent of at least 1 mm aluminum. The material varied depending on the packaging used for the RADFET (kovar or ceramic lids were used).

4.2 Exposure Routine

The routine for rapid irradiation using the RDR100 was as follows:

All devices read normally	pre-irradiation V(T) measurement on Q1 to Q4 including stability and "40uA health checks"
all devices switched to "SHORT"	50 rad(Si) then V(T) measurement on all devices
Repeat above	another three 50 rad(Si) shots giving a total dose of 200 rad(Si);
All devices switched to "STRESS" and value set at +20V	another two 50 rad(Si) shots giving a total dose of 300 rad(Si)
All devices read normally	V(T) measurement on all devices including stability and "40uA health checks"
Repeat next day	to check "Room Temperature Anneal" .

The V(T) shifts were plotted against dose, a log-log plot normally called a "growth curve". The dose values used routinely were from 50 to 500 rads. These curves gave a clear indication of the sensitivity of the device and the degree of linearity achieved in the various modes. Growth curves for a few samples were plotted plotted from 3 to 30,000 rads.

It will be seen that, for some of the exposures at zero bias, the points fall on a straight line with a slope of less than unity on the log-log plot. This implies a non - linear power law, as follows:

$$\mathrm{Delta}V(T) = Z.\ D^{n}$$

where Z is the zero-bias coefficient; n usually lies between 0.6 and 1. The value of n is near to 1 at doses in the 1 to 10 rad region but falls slowly with increasing dose. It is fair to say that the zero - bias reponse is "near linear" at low doses.

The slopes of the growth curves can be used to give responsivity values. The simple method used in this report is to take the total shift value at the intersection of the curve with the 100 rads line. The method is not rigorous but gives figures suitable for comparing trends exhibited by both oxide thickness values in several bias conditions. Another method used by the US Army was to measure the slope of the growth curve at some selected dose value. This is more rigorous but requires a series of standard dose increments at the chosen total dose.

4.3 Definition of Radiation Responses

The clearest expression of the response and nonlinear characteristics of a RADFET is the "Growth Curve" which is simply a plot of the threshold voltage shift (DeltaV(T), herefater abbreviated to "shift") versus dose. For the most common purpose, of assessing radiation sensitivity trends over a wide range, a log Shift - log Dose (Shift vs. Dose on log-log graph paper) is used. This tends to be useful for demonstrating mechanisms of charging and saturation. However sometimes, when a small region of interest must be assessed for nuances of behavior, a linear plot (values of shift versus dose on simple graph paper) is used. Slopes are more easily measured graphically on linear plots.

In this section, we will show a collection of the growth curves taken on this project and comment on significance where appropriate. The Army and its colaborators may find these useful for mathematical analysis or experiment design. One of the objects of future work by the present author would be to further analyse the large amount of basic physical data which is contained in these curves.

The values of shift at 100 rads, divided by 100, are the results usually quoted for "responsivity" in our tabulations. The use of this convention avoids the assumption that all responses are linear. The responsivity at zero bias (gate grounded) is termed r(0); response at +20V is r(+); response for floating gates is termed r(f); response in the "Read" mode is r(R).

4.4 Routine Response Curves for 501A

4.4.1 General

Figs 5 and 6 show growth curves for two 501A wafers, Nos. 1 and 5, which were tested extensively. The results are for a single chip, exposed with the limited bias facilities available at the time. Bias could be altered only on Q4, one of the four devices on the chip; the other three were left floating during irradiation and measured after each exposure. This means that the potential across the oxides of those three were uncontrolled ; the results indicate that they "floated up" to quite a high potential.

4.4.2 "Floated Gate" Effects

In the curves for floated gates, it is seen that the responses are higher than for grounded ("shorted") gates and also have a slope value near to unity up to about 1,000 rad(Si). This provides evidence that a potential is building up on the electrodes and driving electrons out of the oxide.

For later batches, better bias circuits had been built, so that less "float" data was obtained on 501B and C. However, experiments on 501C show a much smaller "floated gate" effect thatn for 501A. The effect is not package-dependent, and these response differences of the floated-gate response in near - identical structures is not understood.

4.5 Trends in the Radiation Response Tests

Table 4 shows that the change to a cleaner 4-inch furnace system for B and C did not have profound effects on radiation response. The important zero-bias radiation response of Type R appears to have fallen in Lot B despite a small increase in oxide thickness and increased again in Lot C. The explanation for this is not known but the effects are fairly small; that is, the responsivity is essentially repeatable from run to run. Moreover, the responsivities of the three wafers so far tested from Lot C are fairly uniform. These two facts serve to fulfil the major objective of the present project - to prove manufacturability of the RADFET.

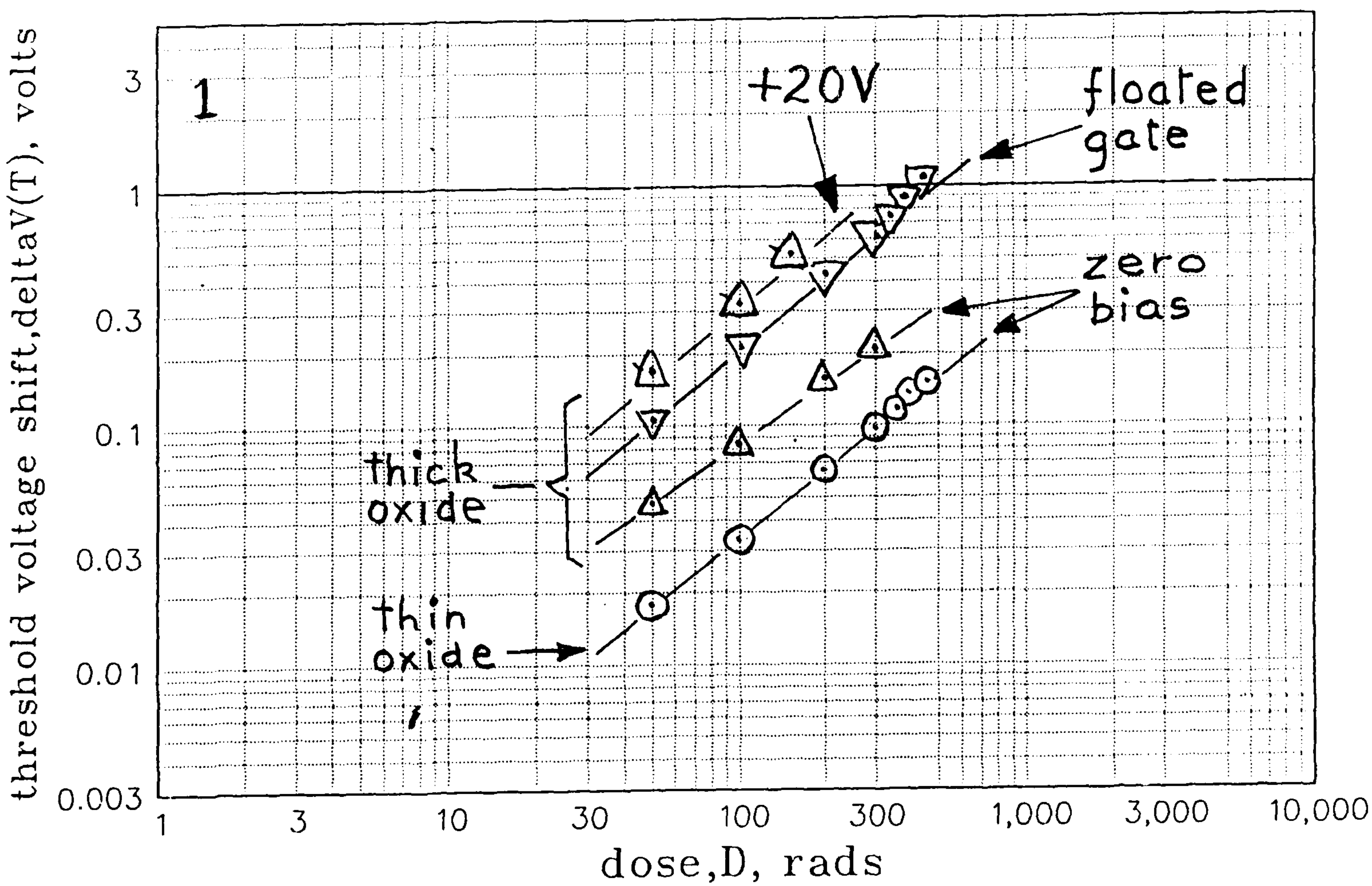

Fig. 5. Experimental radiation response of the TOT500 RADFET as threshold voltage shift versus dose : gamma ray test of single device in various modes. Type TOT501A, WAFER 1

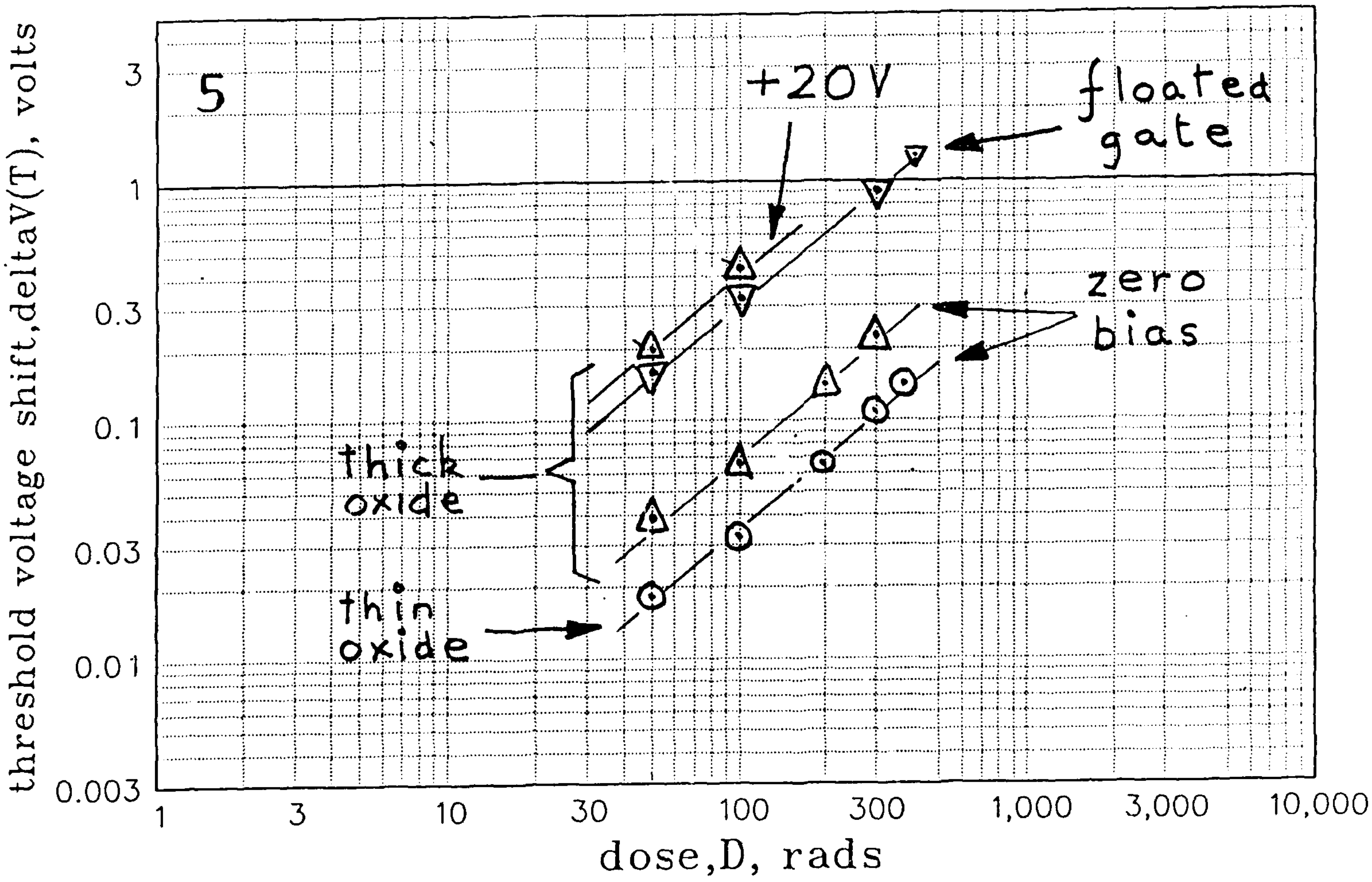

Fig. 6. Experimental radiation response of the TOT500 RADFET as threshold voltage shift versus dose : gamma ray test of single device in various modes. Type TOT501A, WAFER 5

Over the series of runs, we have increased the r(+) values of Type R by increasing the oxide thickness. However, the r(+) value of Type K dropped in Lot 501C, despite an increase in oxide thickness. Variation with package type (Low-Gold vs. Standard) in 501C was not large enough to be detected in the small numbers tested.

4.6 Dynamic Range of RADFET

Fig. 7 shows the nominal performance of the TOT501 RADFET in the tactical range. In fact, it is possible to use the RADFET principle at much higher doses, as has been proved in space experiments now ten years old (Holmes - Siedle and Adams 1985).

Fig. 8 shows a recent example of irradiation of the TOT501C over the range 15 to 30,000 rads at zero bias. After such an irradiation, the thick oxide shows a shift of 11 volts. At these levels, the devices exhibit a large radiation - induced "drift up" when switched from "short" to "Read". However, the physics of this drift is well-known (being due to "slow states") and it saturates if the device is maintained in the "Read" mode. Thus, if the device were read continuously, the drift would not be detectable, although the applied negative oxide field (6 to 10 volts per 0.8 micrometres depending on dose) would modify the responsivity. Earlier experiments in the megarad range showed that threshold voltage shifts continued at a slowed pace up to 10 megarad.

4.7 Low - Dose Responses from 501A and B

Fig. 9 shows an exploratory experiment aimed at obtaining low dose response values for RADFETs. Fulmer's high rate source, consists of a high intensity isotope source which is brought up to one wall of an eight - inch cubic chamber. Low dose rates cannot be obtained. The RADFET system, however, can be regarded as a self calibrating device.

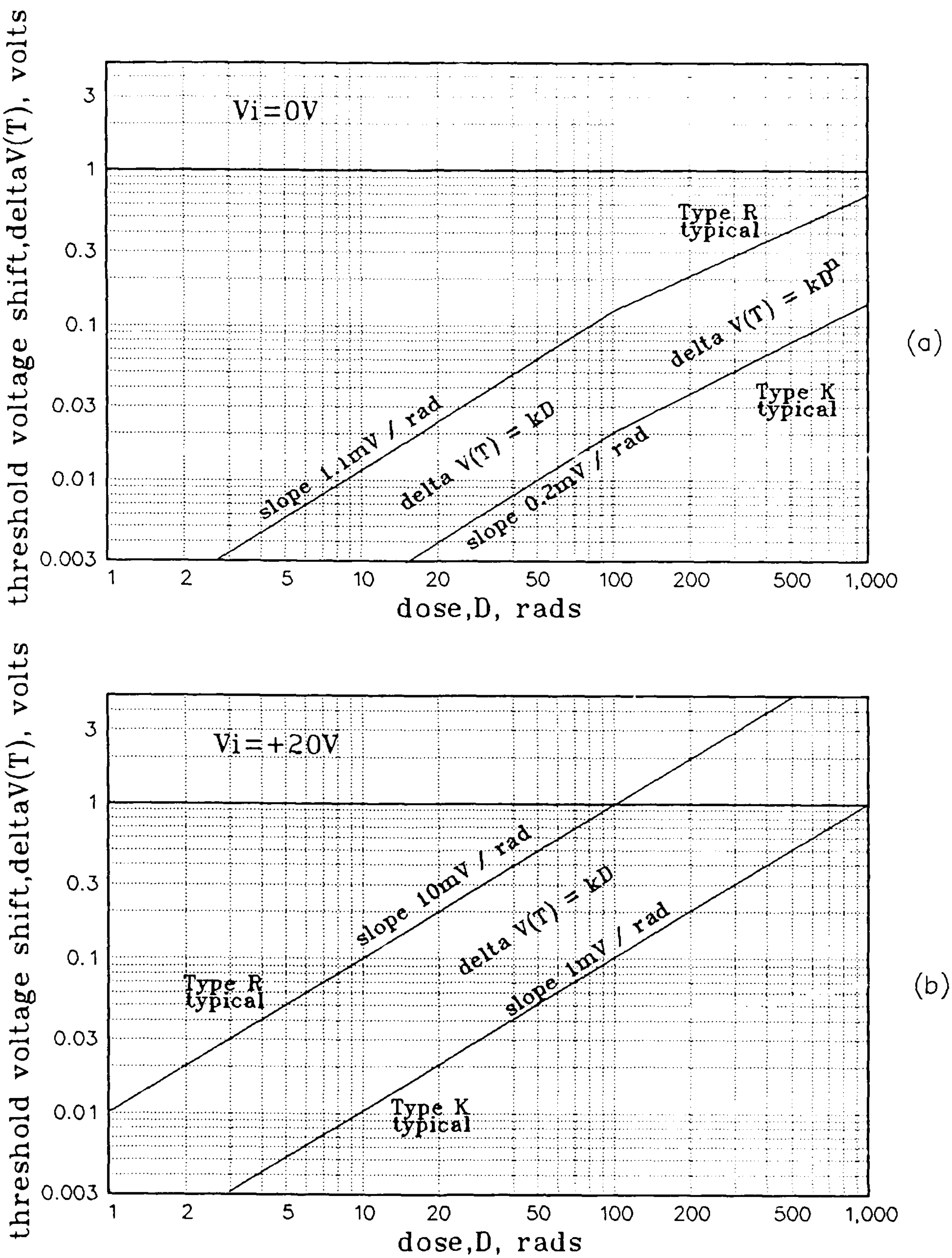

Fig. 7 Nominal response of the TOT501 RadFET for two bias modes
(a) zero bias during irradiation (Vi=0)
(b) positive bias during irradiation (Vi=+20V)

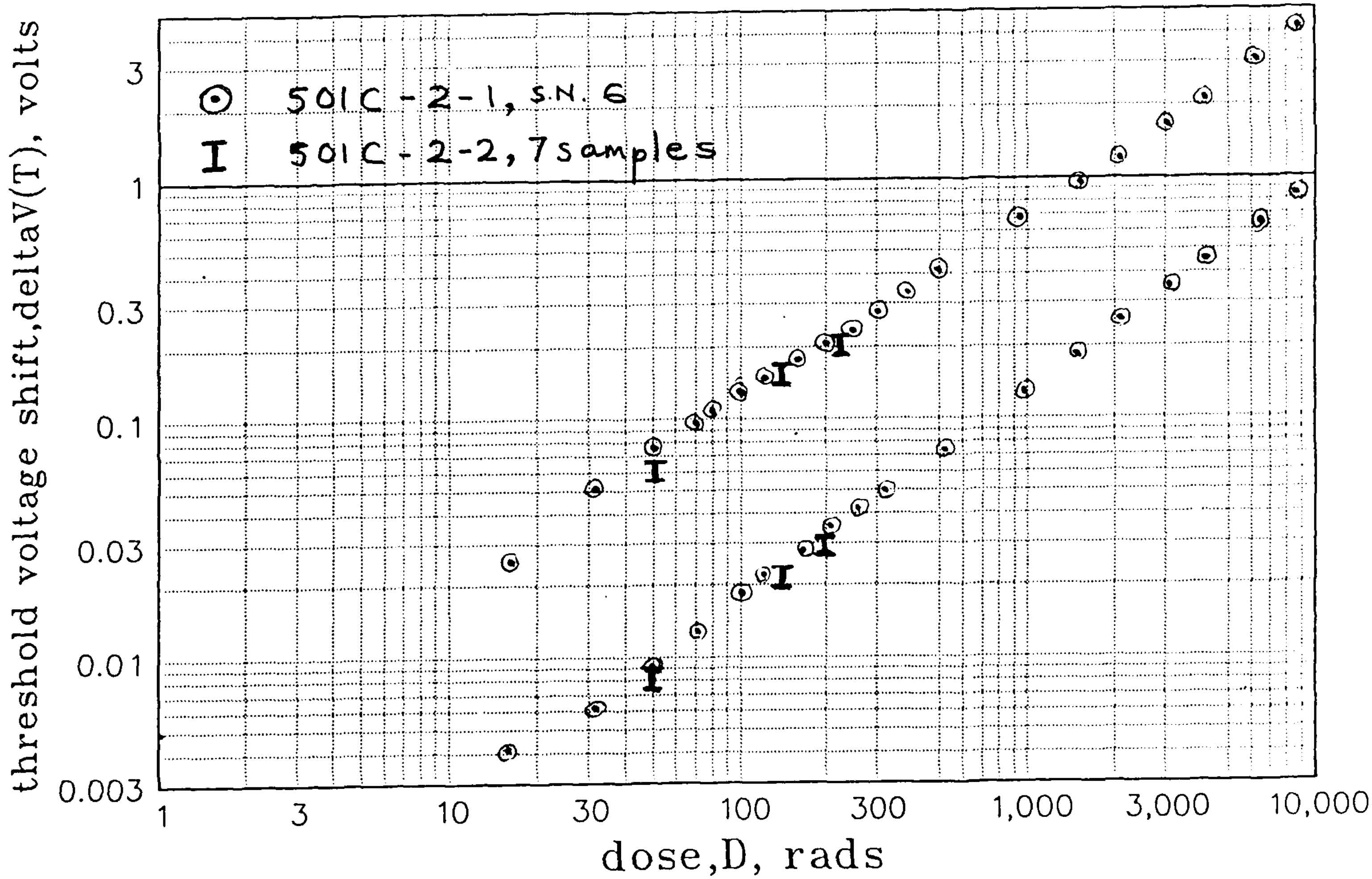

Fig. 8. Threshold voltage shift versus dose for the Type TOT501C RADFET under gamma rays from 50 to 30,000 rad(Si) at ZERO BIAS. Circles - single sample; Bars - seven samples

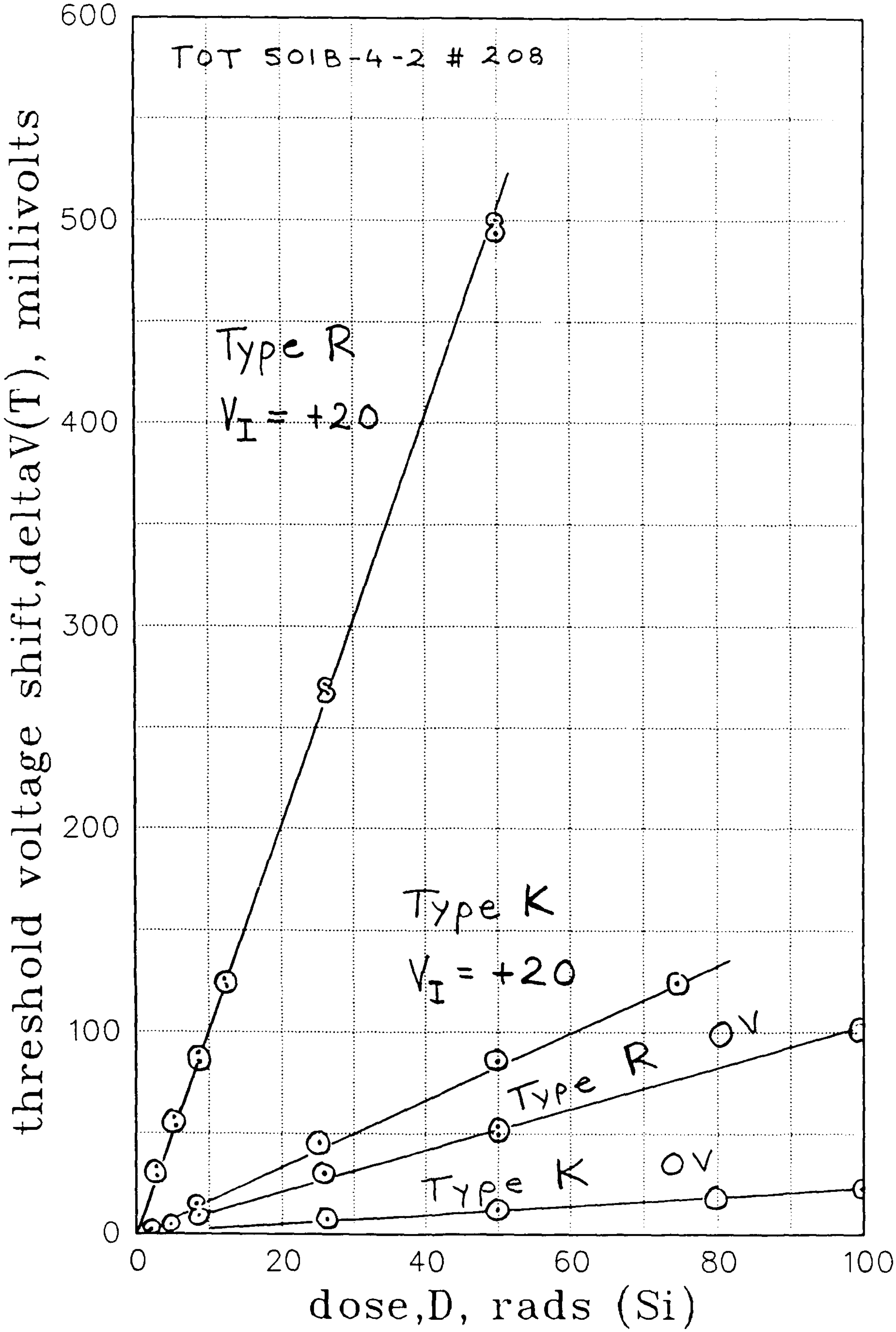

Fig.9 Experimental radiation response of the TOT500 RADFET as threshold voltage shift versus dose : gamma ray test of single device in various modes. Type TOT501B, WAFER 4

A RADFET surrounded with aluminium buildup material was first calibrated at zero bias by several short shots of 25 rads at the normal 2.5 rad/sec. This is the smallest shot obtainable with accuracy at this rate. It was assumed that, for the next 25 rads or so, the responsivity of the RADFET would not vary significantly (i.e. the growth curve was still linear).

Two or three one-inch thick slabs of steel were placed between the source and the RADFET. The shift of the RADFET with time could now be translated into a dose rate in rads(Si), although the radiation spectrum would be altered by the blocks. A dose rate of about 0.4 rad(Si)/sec was calculated for three one inch blocks The attenuation value of 8 was much less than the narrow-geometry figure (about 30 times expected). This suggests that gamma rays are scattered around the edges of the blocks.

In practice, it was found that a series of 10-second irradiations gave 3-millivolt shifts in the Type R (thick oxide) devices in the zero-bias mode. These particular devices had a responsivity of about 1 mV/rad. This exploration of the low -dose regime thus established that, with current RADFET techniques, the lower limit of cumulative dose detectable with the present oxides lies below 3 rads in laboratory conditions. While temperatures were fairly stable, only simple equipment, without noise suppression or drift compensation, was used.

This data also establishes that, in the 1 to 10 rad region, the zero-bias RADFET give a LINEAR response. That is, the "rolloff" effects seen at cumulative doses of hundreds of rads have not yet started in this region. This shows promise for development of millirad measurement with zero - bias RADFETs.

4.8 Statistics of the "Zero - Bias" Response

4.8.1 Results

In Lots 501B and 501C, seven devices from identified blocks on the wafer were irradiated together at zero bias over a range 15 to 200 rads. The values of r(0) varied by plus or minus 5 percent over the whole dose range. A comparison of 3 devices under +20V bias gave a smaller scatter, of plus or minus 1 percent.

This result indicates that, although this spread is of the same order than that seen with competing methods (TLD etc), there is a need for further work to minimise the spread of radiation reponses of oxide films operating at zero applied field, the "Zero-Bias Mode" referred to elsewhere. The physics of the charging effect is not as well worked out as that for the positive=bias mode, where the applied field drives electrons out and leaves a sheet of holes. The source of the "drive" in the zero-bias case is not certain, although R.C.Hughes suggests electron diffusion. Observations from the present run include the following:

- the scatter of r(0) from device to device is larger than for r(+);

- matching of r(0) for the pairs on a die (e.g. the two R devices) is excellent (estimated at 2 percent);

- the ratio between r(+) and r(0) varies greatly from run to run (from 3.9 to 12.3).

It is worth further investigation to determine the reason for the scatter and the limits for its reduction. This would involve the physics of the Si-SiO2 interface and possibly dielectric trapping and transport statistics. One obvious line of research would be to correlate the scatter with that found in the as-processed fixed-charge density (scatter of original threshold voltages). This has a practical aspect, since it affects the amount of mismatch in the original pairs, which is important in differential RADFET schemes.

4.8.2 The Future : Wafer Scale Testing?

An important topic for future work concerns the opportunity for more rapid assessment of zero-bias response ststistics by WAFER SCALE irradiation and probing. One major advantage of the zero-bias mode is that devices do not have to be powered while they are irradiated. A segment of a wafer can be irradiated and returned to the automatic prober on which several hundred devices can be measured in minutes; at this rate, zero-bias growth curves which, in large numbers of assembled devices, would take days to compile, could be taken in hours with wafer irradiation. RADFET devlopment is at the stage now where the trends revealed by such techniques (e.g. yield statistics and die - to - die variations) are critically important.

4.9 Annealing

As with previous RADFETs, room - temperature annealing is less than 5 percent over the week following irradiation. There is some <u>reverse</u> <u>annealing</u> in the first day (see, for example, Ref.8)

We have previously investigated UV annealing of irradiated MOS structure (Emms et al 1974). The TOT500 mask allows for UV - semitransparent aluminium to be deposited in the gate region. However, only two wafers of this design were prepared in (Lot 501A wafer 11 was mounted) but these devices proved rather unstable. Nevertheless, surprisingly, it was found that even TOT501 devices with thick metal over the gate were UV-annealable.

The lids were removed from 501B devices and the effect of exposing these to an EPROM eraser lamp was tested. This UV exposure rapidly lowered the threshold voltage, even before the device had been irradiated. Although the gate metal is thought to be opaque, UV photons are managing to penetrate. Radiation - induced charge was also rapidly erased. This, of course, makes a re - usable RADFET dosimeter possible, although we should expect some non - annealable interface damage to build up.

In the field of thermal annealing, it was found that the chip could be restored by running one of the four devices at over 50 mA. Thermal annealing of radiation - induced charge usually requires chip temperatures above 250 deg.C, so this heating probably cannot be repeated many times. The test establishes the general ruggedness of the RADFET design and why they are rarely destroyed by source - drain overload.

4.10 "Zero Bias" Mode at Low Doses

REM's position on RADFET use is that, wherever the circumstances allow, the RADFET should be used without applied bias. That is, the charge which builds up even when no field is applied to the oxide may in many circumstances be adequate as a measure of dose.

The convenience of the "Zero Bias Mode" of the RADFET is worth while despite the lower responsivity and the non - linearity or "rolloff" in the growth curvea (only important at higher doses). The major argument for this mode is that it eliminates batteries, making "locket", and "badge" approaches to tactical dosimeters more attractive. The advantages in shelf life and general reliability are obvious. Another less obvious advantage is that zero-bias operation avoids the small but significant ion motion which adds error to the biassed mode.

In general, we have been seeing a repeatable zero - bias response of over 100 mV at 100 rads in the Type TOT501 thick oxide (Type R). This is fairly uniform within a production lot (which could contain over 50,000 chips). Over the three wafer runs made so far, the response was very similar from run to run. The question is whether the zero - bias response of Type R, quoted above, is of a magnitude which is adequate for tactical dosimetry. For this, we have to balance the known drift effects and nonlinearity against the ability of advanced circuitry to correct these effects.

Extrapolating from the 100-rad result, the zero-bias mode will give a response of 1 to 2 mV at 1 rad. Given the thermal and other drifts expected in operation, this is not a very large signal to work with. 5 to 10 mV is more desirable. However, the practical experiments quoted above showed that the detection limit certainly lies below 3 rads. Methodology research is needed to determine what is possible in signal processing. The time for this research is ripe now that good samples are available. The opinion of the present author is that mobile charge drift in the oxide provides the limit and that, with suitable circuitry and the optimisation of oxides for zero bias, doses of a few hundred millirads can be resolved.

Using positive bias, a higher response is possible. About 10mV at 1 rad has been demonstrated. Therefore a dose 5 to 10 times can be nmeasured in this mode if we accept the disadvantages of constant battery power and possible long term stress effects of bias in the RADFET. Our chip design philosophy to date has been to leave open both options.

5. PROPOSALS FOR FUTURE DOSIMETER RESEARCH

5.1 General

The future development of the RADFET as a tactical and personnel dosimeter will require several levels of development. These include:

-evaluation of the present deliveries of RADFET TOT501

-dosimeter system development

-advanced RADFET development

-enhancement of the methodology of RADFET use and re-use

This proposal discusses possible further work, including some original ideas for wafer-scale testing and advanced RADFET structures; also a task which ensures that measurements by REM and the US Army will be co-ordinated in future.

5.2 Discussion of Research Needs

The work reported here by REM, along with other independent work by the same author has shown that performance is repeatable but can also be improved by judicious process and package changes. A number if original ideas by the present author are crying out for further work.

While the physics of radiation - induced charge buildup in silicon dioxide films is now fairly well understood for high -doses and electrically powered devices, the physics of the "Zero Bias" method, originated by REM, looks promising but many aspects (e.g. mechanisms of charge buildup and annealing effects) need further study.

In the chip processing area, the work so far has shown that an adequate, repeatable zero-bias response can be achieved. It is now necessary to obtain much more data on the statistics of this reponse (using existing oxide samples) and to explore methods of improving this reponse without increasing interface instabilities at the same time.

A routine for tactical and scientific testing of the TOT500 RADFET will be developed by the US Army. It will be helped by the recent development of a well-engineered test circuit the SILTECH RDR100, tailored to the TOT500 chip. This will be tried out by the US Army in the next few months.

As for the existing thick - oxide dosimeter, Type TOT501, the US Army now has about 400 devices at Fort Monmouth. Before these are passed on to the experimentalists, it is suggested that test procedures be worked out so that REM's future tests and those of the other investigators can be mutually beneficial. It is possible that such work could be planned as a follow - on of the present contract, which concludes with the delivery of a third lot of devices and the present report.

To enhance progress in the next phase (RADFET evaluation) REM suggests a follow-on project in which scientific experiments are done jointly by REM and Fort Monmouth. REM is also prepared to visit other co-operating groups in Europe, the USA and elsewhere. REM's experience with measurement methods and the interpretation of results could assist the program towards a resolution.

5.3 Task Statement

Task 1. PHYSICS OF RADFET CHARGING AND ANNEALING

1.1 Using the TOT500 mask, prepare 3 research batches of RADFET structures likely to measure doses in the range 0.01 to 10 rads gamma rays at zero irradiation bias

1.2 Gamma ray response experiments, including exploration of the "floating gate" effect and use of very low dose increments such as 50 mrad.

1.3 Neutron response experiments including use of hydrogenic films over the chip

1.4 Stability experiments, including trap spectroscopy experiments to identify the source of the "slow states causing "drift up" and reverse fade effects.

Task 2. DEVELOPMENT OF ADVANCED RADFET STRUCTURES

Design study of a Zero - TC / Dose Rate / Total Dose Chip

Task 3. DEVELOPMENT OF AN ADVANCED RADFET ENCAPSULATION

Design and fabricate special RADFET encapsulation and connections (for example an SO8 low - gold package based on epoxy fiberglass with the necessary sockets or leads for quick connection).

Task 4. DEVELOPMENT OF RADFET METHODOLOGY

4.1 Methods of Re - Use

4.2 Enhancement of "Read" circuit stability

4.3 Neutron-gamma dose calculation

4.4 Methods of Wafer - Scale Testing of Zero - Bias Response

Task 5. TECHNICAL ASSISTANCE TO MULTI - CENTRE STUDY

The US Army plans to distribute samples of the REM TOT501 to variouys centres practising dosimetry. REM proposes an expansion of collaborative work with the US Army's contractors and their European collaborators on dosimetry. Seminars and scientific visits in Europe and the USA will be included.

6. CONCLUSIONS

This final report is of a project carried out for the US Army by REM of Oxford, England. The report summarises work on the use of RADFETs to measure radiation dose. A new type of Radiation - Sensitive Field Effect Transistor (RADFET) based on pMOS technology had previously been developed by REM. Three lots of six wafers were processed and tested. Over 450 mounted chips were delivered to the US Army. The silicon wafer fabrication was done by the Industrial Liaison Unit of Southampton University Microelectronics Centre in day - to - day collaboration with REM. Routines to assess these wafers were developed jointly. New low-Z packages were made. REM measured the response to radiation of each lot and made electrical measurements showing that the RADFET was manufacturable in quantity. The "Zero - Bias" method of operation, originated by REM, looks promising. The responses of packaged devices could be made rapidly due to a parallel joint development, between REM and SILTECH, of a benchtop reader.

The Type TOT500 RADFET design showed promise on its very first fabrication run. Now, after three runs, repeatable performance has been demonstrated. It has also been shown that performance can be improved by judicious process and package changes. A change from 3-inch to 4-inch silicon wafers gave improvement.

Now that three sizeable deliveries are in the hands of the US Army, there is an opportunity for a characterisation programme combined with physics research, reader development and further chip and package evolution. The results to date, along with the excellent and voluminous data on similar devices already available from DREO, Canada, fully justify the continued consideration of the RADFET as an element in a tactical dosimeter system. The RADFET is uniquely small, remote reading and integrable with other silicon sensors. A unique possibility which arises out of the present work is that the "zero bias" mode is suitable for tactical dosimetry and civilian accident dosimetry. The elimination of batteries from the sensor part of the dosimeter system is clearly an attractive prospect.

In this report, REM has made some proposals for continued research and development. It is hoped that the US Army will invite the continued collaboration of REM, which, with this final report, has now completed the contractual requirement.

7. SELECTED BIBLIOGRAPHY

7.1 Governmant Reports

1. A. Holmes-Siedle, Process Lot Report No. REM - FM - 88 - 1, "Experimental RADFET Dosimeters ; Report on the First Lot (TOT501A) for Evaluation by the US Army", Contract Number DAJA45 - 87C - 0029 (June 1988)

2. A. Holmes-Siedle, Process Lot Report No. REM - FM - 89 - 1, "Experimental RADFET Dosimeters ; Report on the Second Lot (TOT501B) for Evaluation by the US Army", Contract Number DAJA45 - 87C - 0029 (March 1989)

3. A. Holmes-Siedle, Process Lot Report No. REM - FM - 89 - 2, "Experimental RADFET Dosimeters ; Report on the First Lot (TOT501C) for Evaluation by the US Army", Contract Number DAJA45 - 87C - 0029 (July 1989)

4. S. McGowan "Evaluation of Dual MOSFET Radiation Sensors" Defense Research Establishment Ottawa, Internal Technical Memos (1986 and 1987)

7.2 Published Papers

1. A.G. Holmes - Siedle, "The Space Charge Dosimeter - General Principles of a New Method of Radiation Dosimetry", Nucl. Instrum. Methods 121 169 (1974)

2. A. Holmes Siedle and L. Adams, "RADFETs: A Review of the Use of Metal - Oxide - Silicon Devices as Integrating Dosimeters" Radiation Physics and Chemistry, 28 (2) 235 - 244 (1986)

3. A.G. Holmes - Siedle and L. Adams, "The Mechanisms of Small Instabilities in Irradiated MOS Transistors" IEEE Trans. Nucl. Sci., NS -30 (6) 4135 - 4140 (Dec 1983)

7.3 REM Internal Documents

Note on Copyright and Confidentiality : The documents listed below are proprietary to REM. The documents contain technical information not released publicly. They are made available to clients of REM on request as necessary on the undertaking that they be held "commercial in confidence"

FILE NUMBER "tot....	
500-2	The RADFET Dosimeter [general description](Feb 1988)
501-1	Examples of Statistics from Automatic Probing of RADFETs in Chip and Wafer Form (Feb 1988)
501-2	Measurement Programme "DOT" for V(T) Mapping..HP9845
503-2	Description of the REM Dosimeter System (April 1988)
503-3	Description of an Irradiation Jig for the REM Dosimeter System (April 1988)
503-5	Cables, Probes and Adaptors for the REM Dosimeter System (May 1988)
503-6 to 503-9	Data Sheets for RADFET Dosimeter Accessories, Cables and Probes, Series CAP-100 to 400.
504-1	Packaging of Silicon RADFET chips in 14 Pin DIL (1988)
505-1	Short Specification for the REM Dosimeter Type TOT500 (Spec. No. REM - 88 - TOT505 - 1 (Issue 1) (May 1988)
REM 1984	"REM's Procedure for Selecting and Calibratin' .ADFETs"

A. Holmes - Siedle, REM Report No. TOT - 89 - 1, "User's Manual for the RDR100 Reader" (June 1989) to be modified by SILTECH for issue with the reader.