Sensors and Materials, Vol. 9, No. 6 (1997) 379–386 LETTER
MYU Tokyo

S & M 0299

A Sensitive MOSFET Gamma Dosimeter Fabricated in a Commercial CMOS Process

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(Received May 31, 1996; accepted September 13, 1996)

Key words: MOSFET, dosimetry, gamma, RADFET

Floating-gate metal-oxide-semiconductor field effect transistor (MOSFET) gamma dosimeters have been fabricated in a conventional 1.5 μm gate length commercial CMOS technology. Extension of the floating gate over the field oxide provides good sensitivity without recourse to special processing. Prototype matched-pair dosimeters have shown sensitivities as high as 28 mVGy^{-1} when exposed to a ^{60}Co source. The dosimeter response is linear to within ± 3% for doses in the range of 1 – 10 Gy. Following exposure to a 10 Gy dose, the response was found to increase by ≈ 3% over a period of approximately 24 h before becoming stable.

1. Introduction

MOSFETs have been used as dosimeters for ionizing radiation in a variety of applications for more than twenty years. A typical state-of-the-art MOSFET dosimeter is a p-channel device with a thick gate oxide.(1–3) Radiation generates electron-hole pairs within this oxide. Application of a large positive bias to the gate separates the electron-hole pairs before geminate recombination can occur, and forces the holes to drift to the Si/SiO$_2$ interface, where there is a high probability that they will be trapped. The absorbed radiation dose is inferred from the shift in threshold voltage V_T induced by the trapped hole charge.

The sensitivity of a MOSFET dosimeter is normally defined to be the ratio of the radiation-induced shift in V_T to the absorbed dose. A thick gate oxide is required to obtain high sensitivity to maximize the amount of radiation-generated charge available to be trapped, and to maximize the shift in V_T caused by this charge. With a 1-μm-thick gate oxide, sensitivities in the range of 1 – 1.5 VGy^{-1} have been reported for a gate bias of 20 V. The requirement for a thick gate oxide has, in general, necessitated the use of specialized fabrication processes for the manufacture of MOSFET dosimeters. Specialized processing is costly, and largely precludes the integration of dosimeters with control and readout circuitry on the same chip.

To date there has been one report of MOSFET dosimeter fabrication using a conventional CMOS process.(4) The sensitivity of these devices was very low (only 270 μVGy^{-1}) due to the use of a thin gate oxide. Recently, we proposed a new radiation sensing field effect transistor (RADFET) structure which is compatible with conventional MOS technology, and which provides much higher sensitivity (to 280 mVGy^{-1}).(5) This letter reports the first examples of this new structure fabricated in a commercial CMOS technology. The completed dosimeters were tested by exposure to a ^{60}Co gamma source.

2. Device Structure

The MOSFET sensor structure used here is shown as a cross section in Fig. 1 and plan view in Fig. 2. The structure differs from previously reported RADFETs in that a radiation-generated charge is captured on a floating polysilicon gate rather than by hole trapping at the Si/SiO_2 interface. The floating gate is separated from the overlying control gate by a thin, thermally grown interpoly oxide. The floating and control gates are extended over the field oxide to provide a large volume of oxide from which the radiation-generated charge can be extracted. If a large positive bias is applied to the control gate, radiation-generated electrons from the field oxide will be swept to and trapped on the floating gate. Conversely, application of a negative bias on the control gate leads to hole trapping on or near the floating gate. Since the gate and interpoly oxides are very thin compared to the field oxide, charges generated in these regions can be ignored in a first-order analysis of the device.

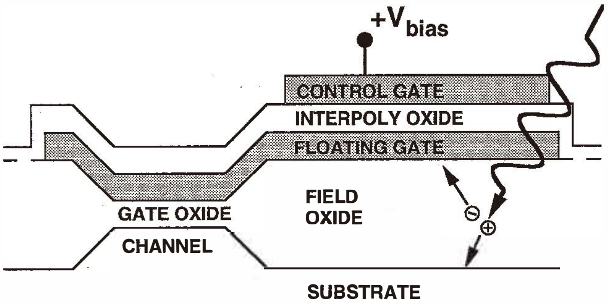

Fig. 1. Cross section of MOSFET gamma dosimeter illustrating the capture of electrons on the floating gate when a positive V_{bias} is applied to the control gate in the sense mode.

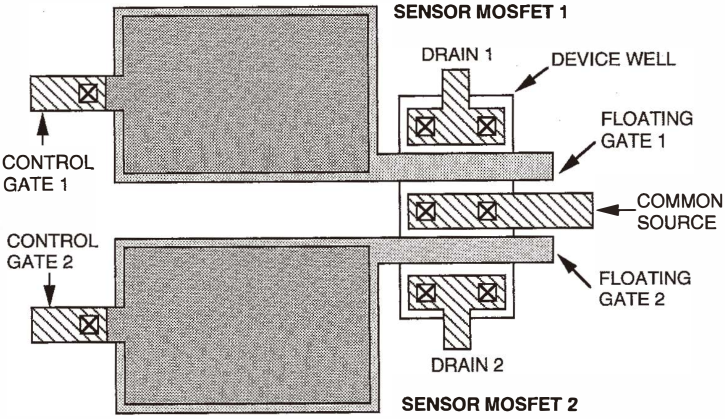

Fig. 2. Plan view of a matched pair of floating gate MOSFET sensors used to construct dosimeter (Not to scale).

The threshold voltage V_T of the sensor is defined as the control gate bias required to give an arbitrarily specified channel current at a given drain-source bias V_{DS}. It is shown[(5)] that if the area formed by the gate extension over the field oxide is much larger than the area of the MOSFET channel, addition of a radiation-generated charge Q to the floating gate alters V_T by an amount determined by:

$$\delta V_T \approx -\frac{Q}{C_i}, \tag{1}$$

where C_i is the capacitance associated with the interpoly oxide.

In any MOSFET dosimeter, it is essential to distinguish shifts in V_T resulting from absorbed radiation from those caused by changes in device temperature. This can be most readily accomplished using a matched pair of sensor MOSFETs and applying different gate biases to the two devices during irradiation.[(6)] The dosimeter output is then the difference in threshold ΔV_T between the two sensors. Application of different gate biases during irradiation leads to differences in the efficiency with which the radiation-generated charge is extracted from the field oxide, so ΔV_T changes on irradiation.

3. Device Fabrication

Prototype matched-pair dosimeters were fabricated as part of a multiproject chip manufactured by Mitel Semiconductor Ltd., of Kanata, Ontario, Canada, in a mixed analog-digital CMOS technology intended primarily for telecommunications applications using 5 V power supplies. The process gives a gate oxide thickness of 27 nm, field oxide thickness of 600 nm and interpoly oxide thickness of 48 nm. Detailed process information is proprietary to Mitel, but one might speculate that the gate oxide would be grown in a dry oxygen ambient and the field oxide in a wet ambient, both at temperatures near 1000°C. The sensor transistors were n-channel devices 1.5 μm in length and 10 μm in width. The area of the gate extension over the field oxide was 50 by 100 μm.

4. Dosimeter Testing

4.1 *Readout circuitry*

A microcomputer-controlled system was constructed to operate the matched pair of sensor MOSFETs as an actual dosimeter. The system allows the MOSFETs to be switched between two circuit configurations: "sense" and "read". In the sense configuration, a positive bias V_{bias} was applied to the control gate of one MOSFET, while the other control gate was grounded. All source, drain and substrate terminals were connected to a common ground while in this configuration. In the read configuration, the circuit shown in Fig. 3 was used to determine the threshold voltage V_T of each sensor. In this circuit an operational amplifier modulated the control gate bias to force the current in each MOSFET channel to equal a reference value determined by the ratio V_{ref}/R_{ref}. An HP34401A voltmeter was used to measure the difference in threshold ΔV_T between the two sensors, which was stored by the microcomputer and displayed as a function of time. The ΔV_T reading was taken precisely 1 s after switching from the sense mode to the read mode, to allow a consistent time for the emptying of the interface traps filled while in the sense configuration. An additional HP34401A voltmeter was used to record V_T for one of the MOSFETs in the matched pair, so that actual thresholds as well as the difference in threshold could be

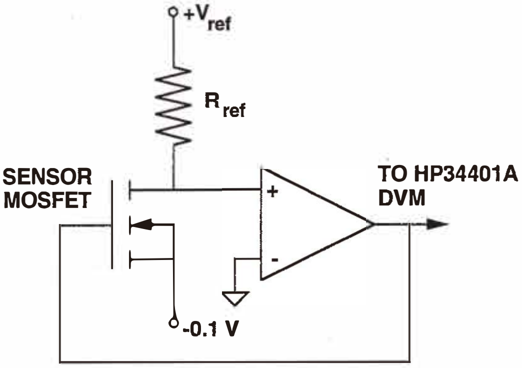

Fig. 3. Circuit used to measure threshold voltage for each MOSFET in a matched pair. Here V_{ref} = 1.2 V, R_{ref} = 100 kΩ.

determined. The read operations were performed 1 time per min, and each took approximately 3 s to complete. The dosimeter system sensitivity was greatly reduced during this 3-s interval, since the gate biases of both MOSFETs in the matched pair were comparable during this period.

4.2 *Stabilization*

When bias was first applied to the MOSFET control gates, ΔV_T was found to drift with time, as shown in Fig. 4. The cause of the drift is uncertain at present, but may be due to charging of border states(7) beneath the field oxide overlapped by the gate extension. The drift results from an increase in V_T for the transistor in which the gate is positively biased while in the sense mode. A similar drift has been observed in dosimeters of similar structure fabricated in a Northern Telecom Electronics Ltd. CMOS technology, and would likely be encountered in other commercial CMOS technologies as well. Figure 4 shows that the drift can be greatly reduced by a conditioning procedure in which V_{bias} is increased beyond its long-term target value for a period of approximately 2 days. Following conditioning, the systematic drift in ΔV_T was reduced to less than 0.2 mV/day for $V_{bias} = 5$ V. The apparently random fluctuation in ΔV_T after conditioning is caused primarily by 1/f noise in the sensor MOSFETs themselves.(8) Over a period of 1 day after conditioning, the standard deviation in ΔV_T is approximately 0.3 mV.

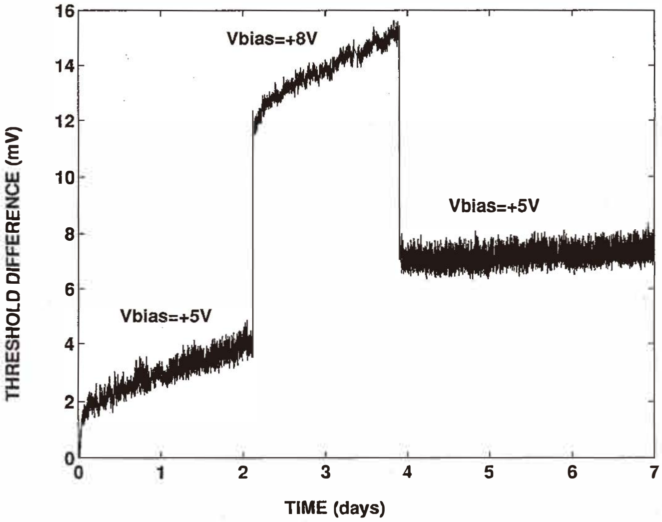

Fig. 4. Drift in threshold voltage difference ΔV_T between MOSFETs in matched pair when bias is first applied. For one device the control gate is held at V_{bias} in the sense mode, while for the other device the control gate is grounded.

4.3 *Radiation response*

To test sensitivity to gamma radiation, the dosimeter was exposed to a 6 kCi ^{60}Co source at a distance of 1 m. A plastic sheet of approximately 5 mm in thickness was positioned directly in front of the dosimeter to serve as a build-up layer. The dose rate for a water sample at this distance has been determined as 0.92 Gy/min. The dose absorbed in the sensor transistors was computed assuming that charged-particle equilibrium had been established by the build-up layer.

Figure 5 shows the evolution of ΔV_T as a function of the absorbed dose for a dosimeter matched pair in which gate biases of + 8.45 V and 0 V were applied while in the sense mode. V_T for the MOSFET with zero gate bias increased slightly during irradiation, but the change in ΔV_T resulted primarily from an increase in the threshold voltage of the device with positive gate bias, as would be expected. ΔV_T changed by 28 mVGy^{-1} on exposure to radiation. The response was linear to within 3% to a dose of 10 Gy. Figure 6 shows that ΔV_T continues to increase for a period of approximately 24 h following exposure, finally saturating at a value $\approx$ 3% higher than that recorded immediately after exposure.

It is of interest to compare the sensitivity measured for the dosimeter described here to that which would be expected on theoretical grounds. Application of a bias of + 8 V to the control gate of a sensor MOSFET gives an electric field of 0.13 MVcm^{-1} in the field oxide. From ref. 9, one would expect that with this field, approximately 40% of the charge generated in the oxide by radiation would be extracted from the oxide and collected on the floating gate. Assuming that an energy of 17 eV is required to form an electron-hole pair in the field oxide, this would give a sensitivity of approximately 40 mVGy^{-1}, roughly 30% greater than that measured experimentally.

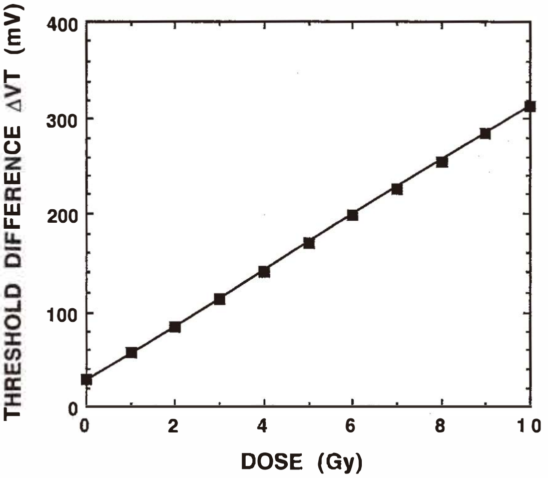

Fig. 5. Change in threshold voltage difference ΔV_T between MOSFETs in a matched pair under irradiation. Dose rate 0.92 Gy/min.

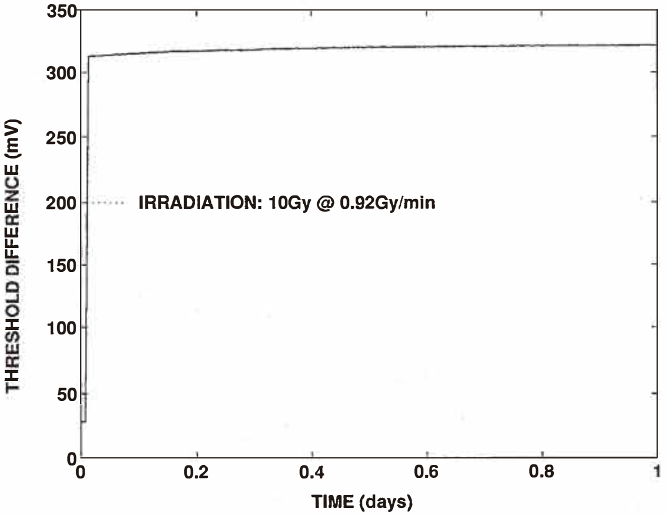

Fig. 6. Evolution of threshold voltage difference ΔV_T as a function of time after 10 Gy irradiation.

5. Conclusion

It has been shown that MOSFET gamma dosimeters with good sensitivity (up to 28 $mVGy^{-1}$), linearity and stability can be fabricated using a conventional commercial double-polysilicon CMOS process developed for telecommunications applications. The dosimeter structure is based on the use of an electrically "floating" polysilicon gate with a large-area extension over the field oxide. This extension is essential for achieving high sensitivity, since it allows the radiation-generated charge to be extracted from the thick field oxide.

Acknowledgements

The authors wish to thank the Canadian Microelectronics Corporation (CMC) for providing multiproject chip access for the Mitel 1.5 process. Financial support for this project was provided by the Canadian Natural Sciences and Engineering Research Council (NSERC) and by the Micronet program of NSERC.

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