

DESIGN CRITERIA FOR A HIGH-DOSE MOS DOSIMETER FOR USE IN SPACE

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ABSTRACT

In a previous paper a small, light-weight, low-power integrating dosimeter is described that is designed for use aboard satellites where the expected total dose is below 30 krad. The radiation-detecting sensors employed are radiation-soft, PMOS transistors. The dosimetric parameter utilized is the shift in threshold voltage, ΔV_T . This voltage shift is related to the radiation dose absorbed, D , in the SiO_2 gate oxide of the transistor. The relationship between ΔV_T and D is determined with a calibrated Co-60 gamma-ray source. The present paper gives experimental results from which design criteria are derived that will extend the use of the dosimeter into the megarad range. The data show that the existing PMOS transistors can be operated in either of two ways. With a high positive gate bias during irradiation, and with some circuit modification, the PMOS transistors are useful up to about 50 krad. When the source, drain, and gate are grounded during irradiation, and subsequently read out normally, the devices are usable up to approximately 2.5 Mrad. The underlying device physics for these two modes of operation is discussed.

INTRODUCTION

The previously described integrating MOS dosimeter (1) developed at the Naval Research Laboratory has the desirable properties of being small, light weight, and low on power consumption, thereby making the instrument well suited for use on satellites. The upper limit on the dose that can be measured with the instrument as designed originally is about 30 krad. With some minor circuit modifications, the upper limit could be extended to approximately 50 krad. However, for employment in parts of the space radiation environment where the integrated dose can equal or exceed a megarad, the manner in which the dosimeter is operated must be significantly modified. In order to clarify how the dosimeter can be operated in either a low or high sensitivity mode, some discussion of the underlying MOS physics is needed.

The original design of the MOS dosimeter is based upon using radiation-soft, p -channel MOS FETs as the radiation sensors (2). The shift in threshold voltage, ΔV_T , is the dosimetric parameter employed in determining the dose, D . The relationship between ΔV_T and D is established with a calibrated radiation source, usually Co-60 gamma rays. The original dosimeter design depends upon hole trapping in the gate oxide as the predominant mechanism for producing the shift in threshold voltage. As pointed out in a previous paper (3), for this mode of operation the gate during irradiation should be biased at a relatively large positive value such that the electric field strength in the gate oxide is 1 MV/cm or greater. The reason for this large gate bias is to minimize errors in the dose measurement that can be caused by charge recombination for radiations that produce in the gate oxide tracks of different charge densities than those of the calibrating radiation. The strong electric field, in effect, pulls apart most tracks expected in the space radiation environment, and, therefore, the differences in response per unit dose are minimized. The point needs to be emphasized that the use of radiation-soft, PMOS transistors is critical for this mode of operation. Such devices have many hole traps produced during fabrication in the gate oxide near the Si/SiO_2 interface. Therefore, hole trapping is the dominant radiation damage mechanism that occurs as a result of the production of electron-hole pairs in the oxide by the radiation. The dominance of the hole trapping results in ΔV_T , which is a measure of the radiation damage, being related in a relatively simple way to D . The radiation-soft, PMOS devices have also been found to exhibit relatively little annealing of the radiation damage (ΔV_T) with time at or near room temperature. The lack of annealing is important for a dosimeter designed to operate in the space radiation environment because of the relatively low dose rates involved and the lengthy times over which measurements are made.

The extension of the positive gate bias mode of operation to the megarad region using the existing sensors is not feasible for several reasons. The currently employed devices have gate oxide thicknesses in the range from 1100 to 1200 angstroms. Extrapolation to the megarad region implies that ΔV_T would be of the order of hundreds of volts. In addition to requiring a completely new circuit design to handle such a large threshold voltage shift, the devices would be expected to suffer electrical breakdown because of the resulting large electric field strength (greater than 20 MV/cm) required to measure V_T .

Since, for devices of the type employed in the MOS dosimeter, ΔV_T per rad varies approximately as the square of the gate oxide thickness, an alternative approach to developing a high-range dosimeter might be to go to very thin oxides. However, the oxide thickness required would have to be approximately 100 angstroms. Such special purpose devices are not expected to be available on a near-term basis. Therefore, to extend the range of the present sensors to the megarad region, another radiation damage mechanism with a low sensitivity is required. This mechanism must also reflect itself in the ΔV_T measurement if the circuit type presently used is to be retained.

Many experiments demonstrate that even when there is a minimum electric field in the oxide of an MOS device there is still a small voltage shift per rad following an irradiation. For devices of the type employed in the MOS dosimeter, this threshold voltage shift is of the order of a few percent of that produced when the gate is biased strongly positive. Therefore, the mechanism producing the small ΔV_T is of the correct order of magnitude to provide a dosimeter usable in the megarad range. Radiation induced *fast* interface state production (4) at the Si/SiO_2 boundary is proposed as the mechanism leading to the small ΔV_T observed in the present work. The results to be discussed are consistent with this interpretation. Tallon (5) reports that when PMOS transistors are irradiated with all elements (source, drain, and gate) grounded, the response (ΔV_T) per rad is independent of the radiations employed (gammas, neutrons, and protons). In using the interface state production mechanism, all elements need to be grounded during irradiation to be assured that there is a minimum electric field in the oxide. With essentially no field present, practically total charge recombination occurs, consequently insignificant hole trapping takes place, and the shift in threshold voltage is due almost entirely to the interface states. Even though the device elements are grounded during irradiation, the threshold voltage is determined after the radiation exposure in the same way as for the positive gate bias mode (1). As pointed out in Ref. 1, V_T is really the negative gate voltage that produces a predetermined constant current from the source to the drain in the FET. The dosimeter circuit automatically establishes this constant current condition, and the associated voltage (V_T) is read out with a digital voltmeter for the laboratory version of the dosimeter used in the present work.

RESULTS AND DISCUSSION

The experimental methods employed are similar to those described previously (3). The collimated, high specific-activity Co-60 gamma source is utilized, and the dose rate is determined with $\text{CaF}_2:\text{Mn}$ TLDs and precise time measurements. The devices employed are fabricated in the United Kingdom (6), and the dosimeter circuit is similar to that described by Adams and Holmes-Siedle (7). The one significant difference in the present work is the irradiation of the PMOS transistors inside of the collimator next to the cobalt pellet when the source is activated. The gamma spectrum is not as clean under these conditions as when the device is irradiated externally to the collimator. The irradiations are done inside of the collimator in order to get the high dose rate needed in the present work. The practical result is that a somewhat larger error associated with the dosimetry results from this procedure.

Device positioning, while fairly reproducible, can also introduce a somewhat greater error than is the case when the FET is irradiated externally at relatively large distances from the collimator exit. In any event, comparison with previous results using external irradiation leads to the conclusion that the total added error is of the order of 20% or less. The purpose of the present work is not to perform precise absolute dosimetry, but rather to obtain reasonably accurate relative results comparing the two modes of operating the PMOS transistors.

Figure 1 gives ΔV_T as a function of dose for three PMOS transistors. As noted earlier, these devices are fabricated in the United Kingdom, hence the designation UK. The device number is assigned arbitrarily in a serial manner, but these transistors are made with microchips from the same Si wafer. The top two sets of data are obtained with positive gate bias during irradiation, whereas the data at the bottom of the figure are taken with a device whose source, drain, and gate are grounded while in the radiation field.

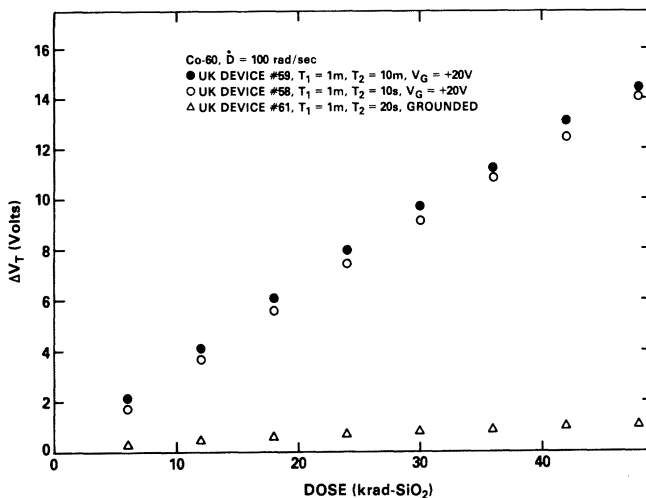


Fig. 1 — The radiation response (ΔV_T) for PMOS transistors under two conditions: gate positive (open and filled circles), and all elements (source, drain, and gate) grounded (open triangles)

The two topmost sets of data in Fig. 1 are designed as a test to determine if *slow* interface state production (8) is observable under conditions in which the devices are used in the positive gate bias mode of operation. If this process were important for the devices employed, then error could possibly be introduced into dose measurements in the high sensitivity (positive gate bias) option. The data represented by the filled circles for device UK # 59 in Fig. 1 are obtained with a different time sequence during which the gate is positive as compared to the data indicated by the open circles for device UK # 58. For both sets of data the irradiation period (T_1) is 1 minute. The dose rate is 6 krad per minute. In the case of UK # 59 the gate is left positive for 10 minutes (T_2) after the irradiation. Making $T_2 \gg T_1$ for UK # 59 is expected to enhance any field-assisted slow interface state production as contrasted to the case for UK # 58 where $T_2 \ll T_1$. If slow interface state production were important under the conditions being compared, the data obtained with UK # 59 would be significantly greater than that taken with UK # 58. While the data for UK # 59 are somewhat higher than that for UK # 58, if individual increments in ΔV_T are computed and compared, the average response of UK # 59 is only 1.5% greater than that obtained with UK # 58. Considering differences in response for individual transistors, of the order of $\pm 2.5\%$, and the uncertainty in positioning the devices in the Co-60 source noted earlier, the conclusion is drawn that slow interface state production is small, and it is not important for the way the PMOS dosimeter is used in practice. The dose rate and timing sequences employed in these measurements are extremes compared to the normal operation of the dosimeter. Also, the gate oxide in these FETs are made by a dry oxidation process, and for such devices slow interface state production is much less than for those fabricated using a wet oxidation method (8). This dependence of interface state production on fabrication method has been attributed to a water-related ion (9). A useful model of the various types of interface states and hole traps is given by Holmes-Siedle and Adams (10). A recent bond strain gradient (BSG)

model (11), supported by x-ray photoelectron spectroscopy measurements, gives a detailed description of the formation of interface states and attempts to show the relationship between the BSG and earlier models.

The data at the top of Fig. 1 for devices UK # 58 and UK # 59 also illustrate the limited range in dose that is accessible in the positive gate bias mode of operation. Note that the total shift in V_T is approximately 15 volts for a dose of 50 krad. At the bottom of the figure, and shown by open triangles, the data for device UK # 61 demonstrate the much lower response that results when the device is irradiated with all elements grounded and then read out in the usual way after irradiation.

A more extensive range of ΔV_T as a function of D for device UK # 61 is given in Fig. 2. The open circles are the experimental results, and the dashed curve is a least-squares fit to these data. In the relationship obtained from this analysis, $\Delta V_T = 0.0832 D^{0.662}$, ΔV_T is in volts and D in krad. The data in Fig. 2 show that for a dose of 1.1 Mrad the total shift in V_T is only 8 volts. By using the approximate $D^{2/3}$ relationship to extrapolate, for a 15 volt shift in V_T the corresponding dose is 2.5 Mrad.

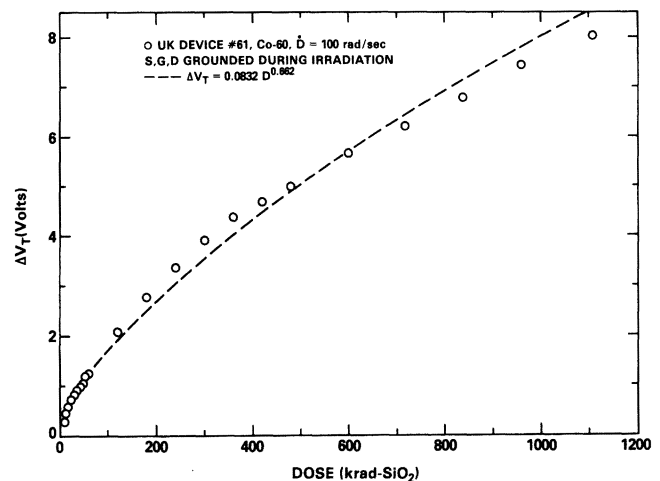


Fig. 2 — A more extended range of ΔV_T as a function of dose for a PMOS transistor irradiated with all elements grounded. The dashed curve is a least-squares fit to the data.

The approximate $D^{2/3}$ dependence of the shift in V_T with dose is characteristic of interface state production (8). At the present time a fundamental understanding of this (2/3)-power dependence does not appear to exist. This relationship rests primarily on experimental data, although McLean (9) gives a speculative argument as to the reasonableness of the (2/3)-power result. For the UK # 61 data in Fig. 2, the shift in threshold voltage is attributed to *fast* interface state production, which in turn, is associated with the breaking of chemical bonds in SiO_2 near the Si/SiO₂ boundary (10,11). The breaking of chemical bonds under minimum electric field conditions in the oxide makes the results of Talion (5) (the independence of ΔV_T per rad with radiation type) understandable.

CONCLUSIONS

The data presented lead to useful design criteria for extending the dose range of the PMOS dosimeter discussed in Ref. 1. Other available oxide thicknesses are being investigated in order to obtain additional sensitivities for both the grounded elements and positive gate bias modes of operation. Work is being started on modifying the circuit given in Ref. 1 in order to operate one or more sensors in the grounded elements mode.

A final comment needs to be added in order to emphasize that the use of the PMOS transistor with all elements grounded provides a simple dosimeter that can operate in the difficult to reach megarad range. By way of comparison, note that the response curves for the more commonly used TLDs (12) become double valued at doses greater than 50 to 100 krad. While the PMOS dosimeter results discussed are aimed at employment in space, a megarad dosimeter has many applications in other areas. Usage in device testing for total dose radiation hardness is but one important example.

ACKNOWLEDGMENTS

The author wishes to thank J. C. Ritter for his continuing interest in and support of this work. Useful discussions with A. Holmes-Siedle and his efforts in helping to obtain the PMOS transistors are gratefully acknowledged. This research is funded by the Naval Electronic Systems Command, Code 615, under the NRL/NAVELEX Spacecraft Survivability/Vulnerability Program.

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