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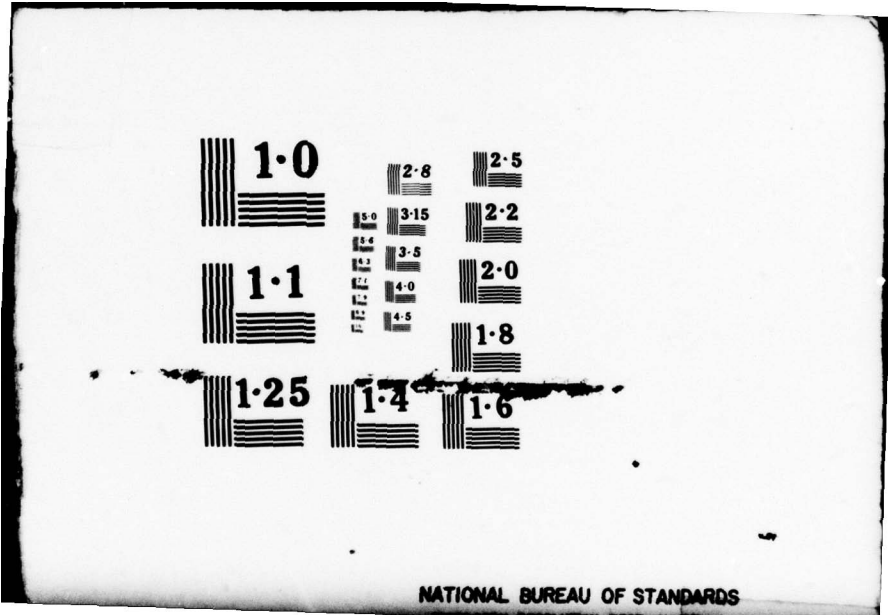
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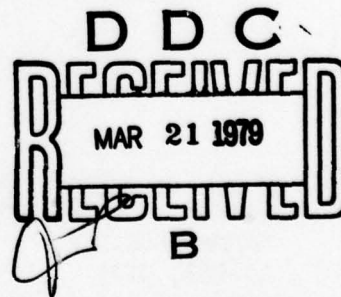
METAL-NITRIDE-OXIDE-SEMICONDUCTOR
DETECTOR FOR AN IONIZING
RADIATION DOSIMETER

Ronald G. Fraass, Capt, USAF

October 1978

Final Report

Approved for public release; distribution unlimited.



AIR FORCE WEAPONS LABORATORY
Air Force Systems Command
Kirtland Air Force Base, NM 87117

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This final report was prepared by the Air Force Weapons Laboratory, Kirtland Air Force Base, New Mexico, under Job Order 88091134. Capt Michael G. Knoll (ELP) was the Laboratory Project Officer-in-Charge.

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number): This report describes the work completed by Capt Fraass for his Master of Science thesis at the Air Force Institute of Technology. The topic and funds for this Master's work were provided by the Air Force Weapons Laboratory. A method of radiation dosimetry using a Metal-Nitride-Oxide-Semiconductor (MNOS) device as the detector was developed and partially evaluated. The MNOS devices are capable of measuring doses from 10 krds to 4 Mrds. Repeatability of observations indicates a precision of ± 1 percent of total dose from 200 krds to			

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4 Mrds (Si). Dosage in rads (rds) is obtained by reference to a calibrated source exposure rate and not to dose absorbed within the dosimeter. A Co^{60} source was used for all radiation testing. Schematics are given for some of the circuits tested. Determination of dosage from the system is indirect and requires the use of a calibration curve. Each dosimeter must be calibrated from a known source. Direct readout of dose is suggested by use of a microprocessor. Exposure to 2×10^7 rds did not degrade performance. Devices eventually failed due to charge migration from the large integrated circuit chip on which they were fabricated. Discrete, nonstepped gate MNOS transistors are recommended.



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PREFACE

This report summarizes my investigations into the use of a Metal-Nitride-Oxide-Semiconductor (MNOS) as the detector for a high dose level radiation dosimeter. I terminated my research after completing a partially automated dosimeter. Further work is needed to bring the dosimeter to the production stage. A small microprocessor should be added to allow a direct readout of radiation dose. At its present stage of development the dosimeter reading is used in conjunction with a graph to give a value of radiation dosage.

This research was sponsored by the Transient Radiation Effects Branch of the Air Force Weapons Laboratory (AFWL/ELP), Kirtland Air Force Base, New Mexico.

For their encouragement and support, I am indebted to my advisors, Dr. George John and Dr. Richard Hagee. Roger Talion of the AFWL was instrumental in the procurement of the MNOS devices and in initial circuit design. The technicians of the Air Force Institute of Technology (AFIT) Physics Department assisted in circuit fabrication.

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SECTION I
INTRODUCTION

A direct readout method of radiation dosimetry was desired for certain experimental work at the Air Force Weapons Laboratory (AFWL), Kirtland Air Force Base, New Mexico.* The experimental work required determination of radiation dosages in semiconductor materials which were irradiated with a pulsed X-ray or electron beam machine. These irradiation methods require that the target materials be in a vacuum chamber. Most standard dosimeters, such as the Thermoluminescence dosimeter (ref. 1) or Ceric Sulphate dosimeter (ref. 2) need to be removed from the target chamber after each dose to determine the radiation dosage. The removal procedure meant a delay of several hours between pulses. This lengthy delay included time for reading the dosimeter and time to again achieve the desired vacuum in the target chamber. If an accurate dosimetry technique were available which permitted direct electrical readout of dose, the delay between radiation tests could be greatly reduced.

The AFWL suggested that one possibility for such a dosimeter might be based on the use of a Metal-Nitride-Oxide-Semiconductor (MNOS) transistor.* Therefore, the purpose of this experimental study was to determine the feasibility of using an MNOS transistor as the detector in a radiation dosimeter.

MIS DOSIMETRY

The use of an MNOS as a dosimeter follows from dosimetry methods using similar devices. The MNOS transistor is a member of the Metal-Insulator-Semiconductor (MIS) family. Other better known members are the Metal-Oxide-Semiconductor-Field-Effect Transistor (MOSFET) and the Metal-Oxide-Semiconductor Capacitor (MOSC). Use of the MIS family of devices as dosimeters is possible

*Knoll, M. G., "MNOS Dosimeter," Proposed Thesis Topic. Air Force Weapons Laboratory, Kirtland Air Force Base, New Mexico, May 1977.

1. Holm, N. W. and R. J. Berry, Manual on Radiation Dosimetry, New York, Marcel Dekker, Inc., pp. 397-409, 1970.
2. Church, V. E., et al., "Direct Readout Instrument for Gamma Dosimetry," Scientific Instruments, March 1976, pp. 182-186.

since radiation produces measurable effects in each of these devices. Radiation dosimeters have been designed using both the MOSFET (ref. 3) and the MOSC (ref. 4).

A problem with the MOSFET and MOSC dosimeters is the semipermanence of the radiation effects in both (ref. 5, p. 1270). This problem prevents individual calibration of a given dosimeter. Lack of individual calibration limits precision to ± 5 percent when devices from a single semiconductor wafer are used. If devices from different wafers are used for calibration, the precision drops to ± 20 percent (ref. 4, p. 351).

An alternative to the MOSC and MOSFET is offered by the MNOS. Its characteristics are similar to those of the MOSFET with one major difference. The electrical characteristics of the MNOS, which are altered by radiation, can be returned to their preirradiation values through the application of a proper electrical signal (ref. 6). Since radiation effects are not permanent in the MNOS, a dosimeter incorporating an MNOS could be individually calibrated to permit a high precision.

A possible further advantage of the MNOS is its greater hardness to radiation effects. The MOSFETS used by Poch and Holmes-Siedle showed saturation dose effects at 4×10^4 rds(Si) (ref. 3). Studies of the radiation hardness of MNOS memory arrays (ref. 6, p. 186) have shown that saturation effects did not occur until 3×10^6 rds(Si). Consequently, an MNOS dosimeter could measure doses nearly two orders of magnitude higher than the MOSFET dosimeter.

SCOPE OF THE PROBLEMS

The primary purpose of this experimental study was to determine the feasibility of using an MNOS transistor as a radiation dosimeter. If the MNOS were shown to be usable as a dosimeter, the design and characteristics of an MNOS dosimeter were to be studied.

The scope of this problem was limited to the study of a group of MNOS transistor devices before and after their exposure to Co^{60} radiation, and the study of an MNOS dosimetry method which requires manual operation and graphical determination of radiation dosage. Study of the manual dosimetry system

NOTE: References 3, 4, 5 and 6 are listed on reference page in back of the report.

included determination of minimum measurable dose, maximum measurable dose, and precision. Final design of a fully automatic MNOS dosimeter was considered to be beyond the scope of this study.

APPROACH

Verification of the MNOS dosimetry concept began with a study of the characteristics of the MNOS transistor. The general results of that study are shown in Section II. Once the general theory of the MNOS devices was understood, electrical circuitry had to be designed to allow testing of the MNOS devices. Section III includes a description of the devices tested, the experimental set-up, and the testing procedures used on the MNOS devices. Since the test circuit was able to measure the effects of radiation on the MNOS devices, it was, in effect, a manual operation dosimeter. The results of testing the manual dosimeter for dose limits and precision are shown in Section IV. Section V presents the conclusions of this study and includes some recommendations for further development of an automatic MNOS dosimeter.

SECTION II

MNOS THEORY

Much of the theory concerning the MNOS detector deals with its use as an electronic memory. The MNOS was developed as an attempt to produce a better MOSFET. One of the principal characteristics of the MOSFET is a fixed threshold voltage. When the early MNOS devices were tested for threshold voltage, unexpected results were obtained. The threshold voltage was found to be variable and dependent upon the electric field previously applied from gate to substrate. This variable threshold voltage gave rise to the use of the device as an electronic memory.

Radiation degradation of the information stored in an MNOS memory unit led to its consideration as a radiation detector. In order to design an MNOS detector, a general understanding of the characteristics of the device is required. This section describes the basic MNOS device, its operation, charge transport mechanisms, effects on stored charge by time and radiation, and the read-disturb effect.

MNOS

The MNOS transistor is an Insulated-Gate-Field-Effect-Transistor (IGFET), similar to the MOSFET. However, it has a double layer of insulator material. Figure 1 is a diagram of a p-channel enhancement-mode MNOS transistor. The substrate, 200 μm thick, is lightly doped n-type silicon. The source and drain are both heavily doped p-type regions. A gate region is above and between the source and drain. The gate region consists of 20 \AA of SiO_2 covered by 500 \AA of Si_3N_4 . Metalized contacts are provided for electrical connections to the drain, source, gate, and substrate.

OPERATION

The operation of an MNOS transistor is dependent on the voltage applied to the gate and drain. For the p-channel enhancement-mode device in figure 2, current will flow between source and drain when a sufficiently negative voltage is applied from gate to substrate, V_{GS} . The negative voltage on the gate pulls holes up to the silicon/silicon-dioxide interface. The holes in the formerly

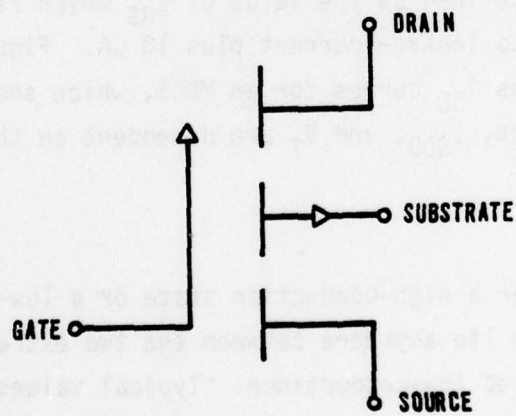
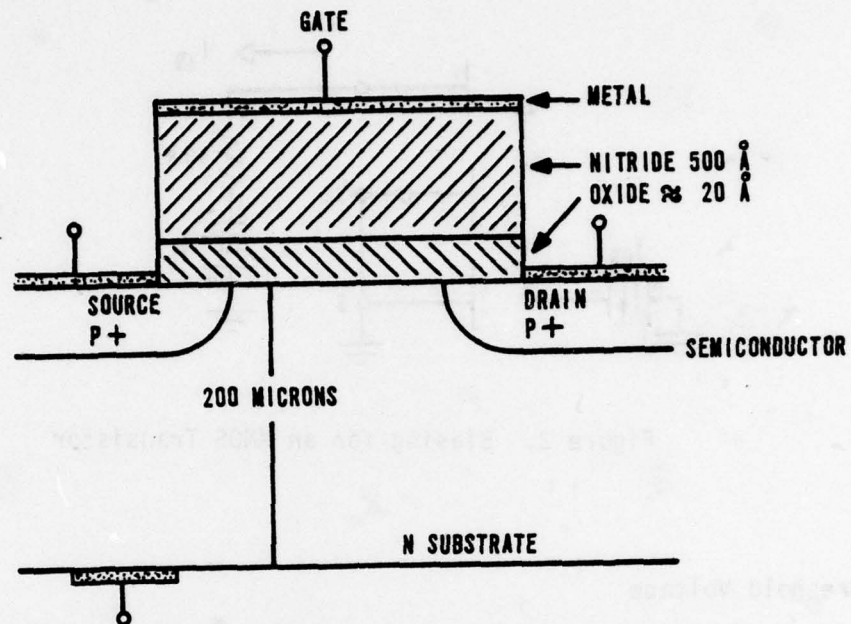


Figure 1. P-Channel Enhancement Mode MNOS Transistor and Symbol

n-type material form a conduction channel between the source and drain. This channel permits a current to flow from source to drain.

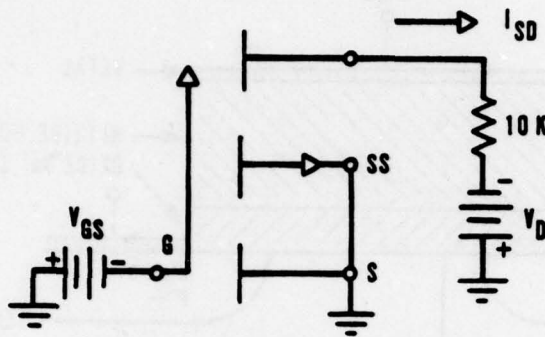


Figure 2. Biasing for an MNOS Transistor

Threshold Voltage

A variable threshold voltage, V_T , is a characteristic of an MNOS which distinguishes it from an MOS transistor. Threshold voltage is defined as the value of V_{GS} which permits a defined amount of source-drain current, I_{SD} , to flow. For this experiment V_T was defined as the value of V_{GS} which resulted in a total source-drain current equal to leakage current plus $10 \mu A$. Figure 3 is a generalized set of V_{GS} versus I_{SD} curves for an MNOS, which shows that the values of the leakage current, I_{SD0} , and V_T are dependent on the conduction state of the device.

Conduction State

The MNOS may be in either a high-conduction state or a low-conduction state. The V_{GS} versus I_{SD} curve can lie anywhere between the two extremes of saturated high-conductance and saturated low-conductance. Typical values of V_T might be -0.4 volt in the high-conduction state and -11 volts in the low-conduction state. The magnitude of threshold voltage in the high-conduction state, V_{TH} , is always less than the magnitude of the threshold voltage in the low-conduction state, V_{TL} . The third curve in figure 3 shows the point V_{T0} . After sufficient time, the I_{DS} versus V_{GS} curves move from either saturated condition to that middle curve. V_{T0} may be called a stable threshold voltage because it does not change

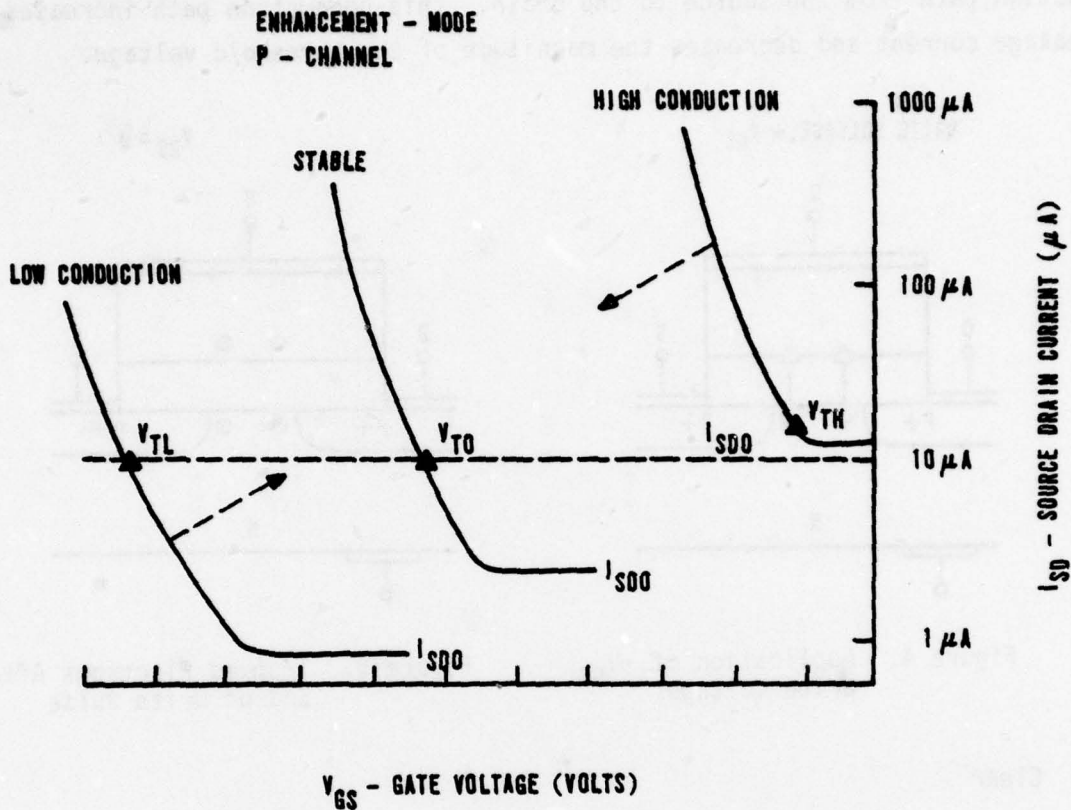


Figure 3. Generalized Curves for Source Drain Current (I_{SD}) Versus Gate Voltage (V_{GS})

with time. The difference between V_T in a low- and high-conduction state depends upon the amount and polarity of charge stored in the device at the silicon-nitride/silicon-dioxide interface.

Writing

Placing additional negative charges at the interface is defined as writing. A saturate write pulse for a p-channel enhancement mode MNOS is a positive V_{GS} pulse. It must be of sufficient magnitude and duration to put the device into a saturated high-conduction state. During the application of the write pulse, as seen in figure 4, electrons penetrate the thin oxide by a tunneling process and enter deep traps in the silicon-nitride near the boundary of the nitride and oxide layers. Saturation occurs when the field across the oxide due to trapped charge equals the field due to the externally applied V_{GS} . Once the write pulse is removed, as shown in figure 5, the stored negative charge draws holes from the

substrate to the substrate/oxide interface. These holes partially open a conduction path from the source to the drain. This conduction path increases the leakage current and decreases the magnitude of the threshold voltage.

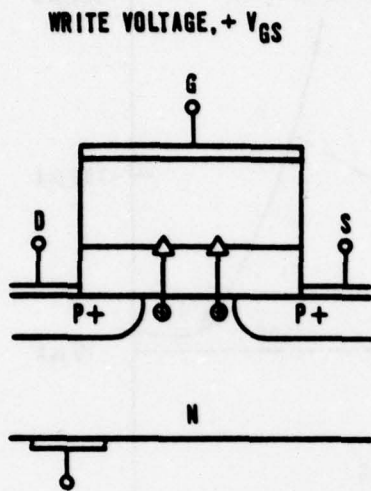


Figure 4. Application of $+V_{GS}$ Write Voltage

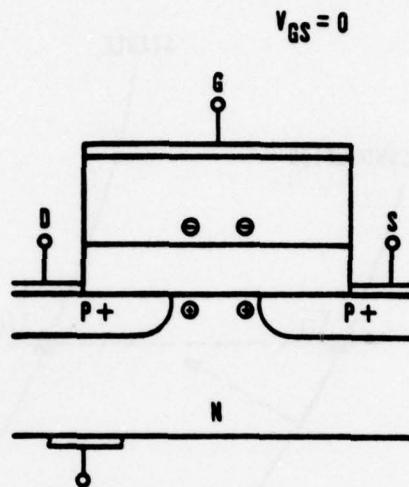


Figure 5. Trapped Electrons After End of Write Pulse

Clear

During a clear operation, as shown in figure 6, a negative V_{GS} pulse is applied. This causes trapping of holes in the nitride at the nitride/oxide interface. After the clear pulse ends, the trapped holes pull free electrons to the surface in the substrate as shown in figure 7. The excess electrons effectively block the conduction path between source and drain. Leakage current is therefore reduced and the magnitude of V_T increases.

MECHANISMS

A more detailed discussion of the mechanisms of charge transport in and characteristics of the MNOS is given by Frohman-Bentchkowsky (ref. 7) and by Lundstrom and Svensson (ref. 8). Lundstrom and Svensson indicate that modified

7. Bentchkowsky, D. F., "The Metal-Nitride-Oxide-Silicon (MNOS) Transistor - Characteristics and Applications," Proceedings of the IEEE, 58, pp 1207-1219, August 1970.
8. Lundstrom, K. I. and C. M. Svensson, "Properties of MNOS Structures," Transactions on Electron Devices, Ed-19, pp 826-836, June 1972.

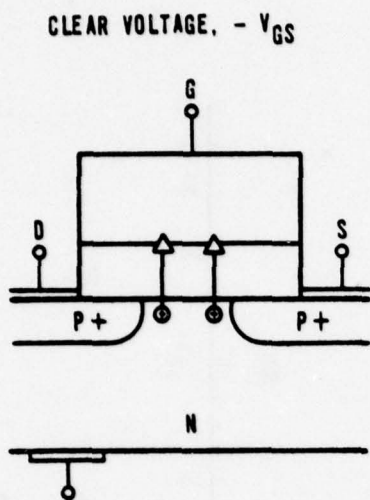


Figure 6. Application of $-V_{GS}$ Clear Voltage

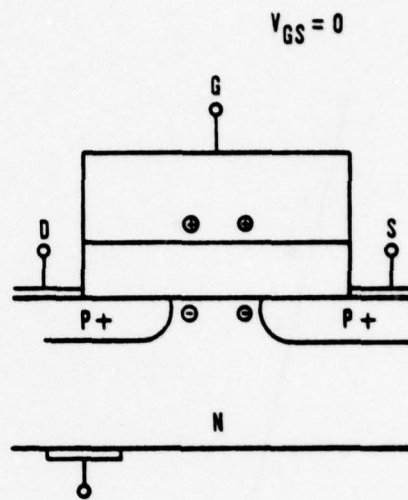


Figure 7. Trapped Holes After End of Write Pulse

Fowler-Nordheim tunneling may be the mechanism for transport of charge through the oxide when high external fields are applied and the oxide is thin (ref. 8, p. 829). Fowler-Nordheim tunneling is based on the quantum physics principle of tunneling. The Fowler-Nordheim expression is modified by Lundstrom and Svensson to include specific probabilities for transmission of carriers through the oxide and nitride.

However, charge transport continues after the removal of V_{GS} . This continued charge transport is controlled by the internal fields due to the trapped charge carriers. The charge transport, due to recombination, tends to neutralize the stored charge after sufficient time.

TIME EFFECTS

The changes in V_T with time are seen in figure 8. The threshold voltage can be seen to be linear in $\log(t)$ at least out to 10^3 minutes. The curve for a device initially in the low-conduction state is similar (ref. 6, p. 63). The dependence of V_T on stored charge seen from the time effects is also the basis for the primary radiation effects in MNOS.

RADIATION EFFECTS

Radiation induced changes in an MNOS are due primarily to the effects of electron-hole pairs, produced by the radiation. Incident gamma radiation (Cobalt 60) produces Compton electrons which in turn produce electron-hole pairs.

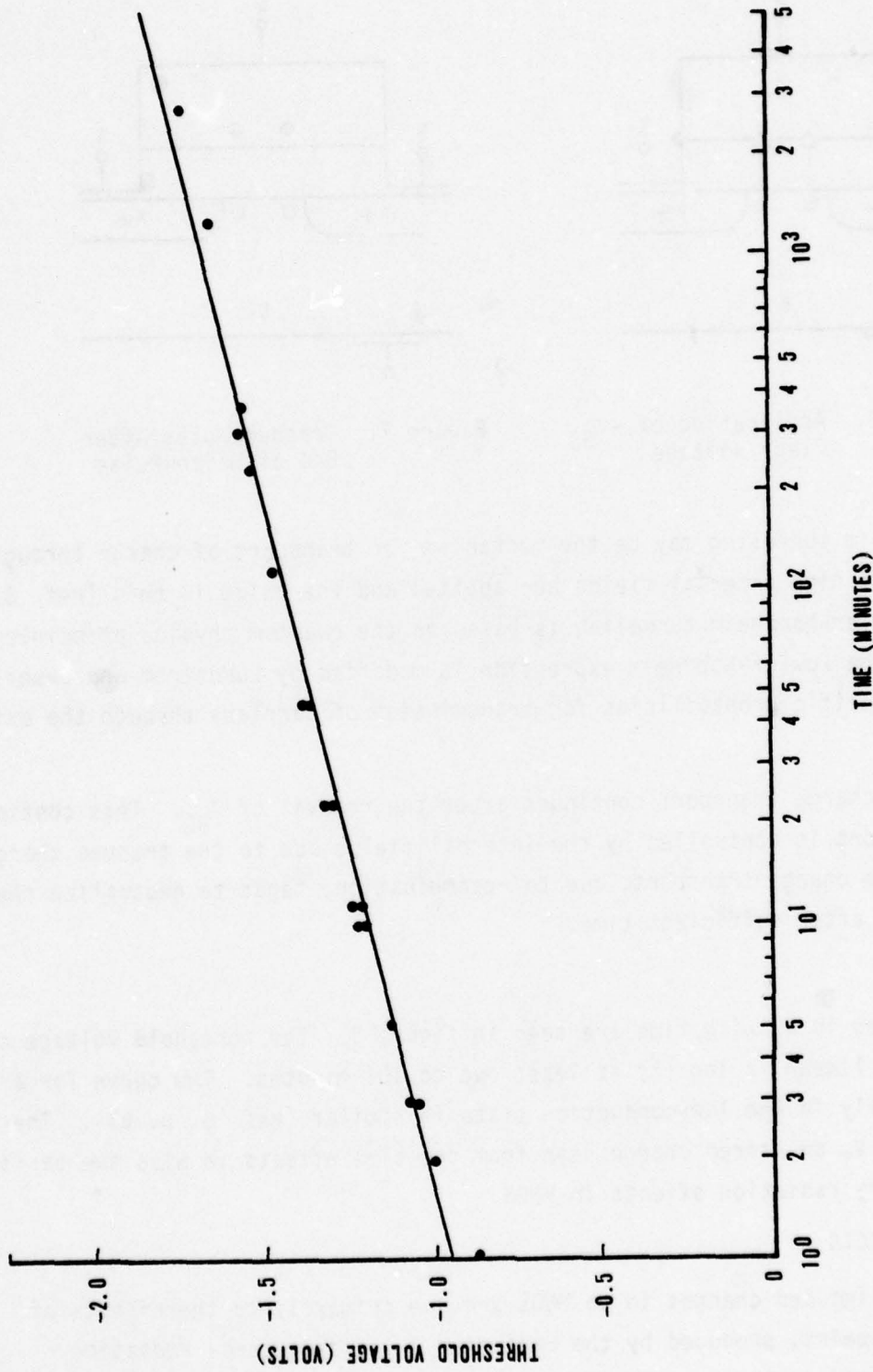


Figure 8. MNOS Threshold Voltage Versus Time

These free charge carriers move through the oxide under the influence of the internal electric fields produced by the trapped carriers in the silicon-nitride. They then recombine with the trapped carriers to reduce the stored charge and cause the threshold voltage to change.

Theory

An empirical equation has been developed which relates the threshold voltage in an MNOS transistor to absorbed radiation dose. The theory leading to the equation is shown in appendix I of reference 6. The development proceeds from the basic relationships between applied field, space charge, and current in an insulator; and then assumes a radiation induced change in space charge based on ohmic conduction in the insulators. A portion of that development is presented here.

The nitride and oxide layers of an MNOS gate are modeled as a two-layer insulator as in figure 9. A thin layer of charge σ is assumed to lie in a plane at the nitride-oxide interface. The relationship between σ , the nitride field E_n , the oxide field E_o , and the applied voltage V_G is as follows:

$$E_n x_n + E_o x_o = V_{GS} \quad (1)$$

$$\epsilon_o E_o - \epsilon_n E_n = \sigma \quad (2)$$

where ϵ_n and ϵ_o are the dielectric permittivities of the nitride and oxide layers, and x_n and x_o are the thicknesses.

It is assumed that the value of σ at the interface is responsible for changes in V_{FB} , the flatband voltage. The flatband voltage is that value of V_{GS} which results in $E_o = 0$. Putting this relationship into equations (1) and (2) yields

$$V_{FB} = -\sigma \frac{x_n}{\epsilon_n} \quad (3)$$

Equations (1), (2), (3) then may be solved for E_n and E_o :

$$E_o = \gamma \epsilon_n (V_{GS} - V_{FB}) \quad (4)$$

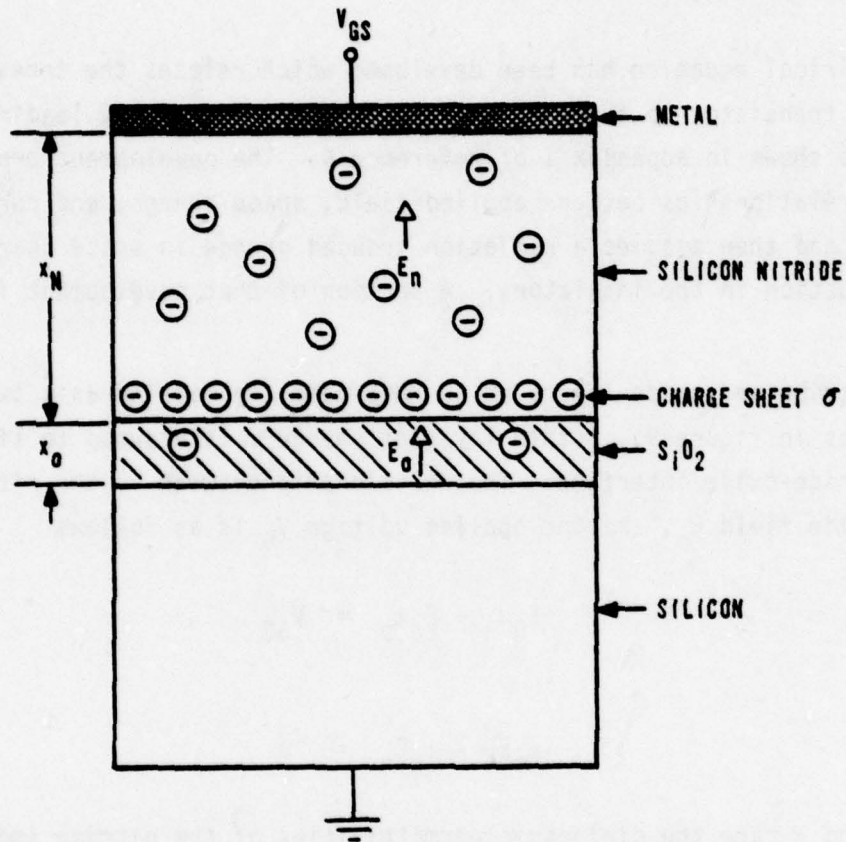


Figure 9. MNOS Gate Region (from ref. 6, p. 187)

$$E_n = \gamma \epsilon_0 (V_{GS} + \beta V_{FB}) \quad (5)$$

where $\gamma = (\epsilon_n x_o + \epsilon_o x_n)^{-1}$ and $\beta = \epsilon_n x_o / \epsilon_o x_n$. Equations (4) and (5) are valid for E_o and E_n at any instant of time. To determine V_{FB} as a function of time requires the use of the equation of current continuity for the system.

$$\epsilon_o \frac{dE_o}{dt} + j_o = \epsilon_n \frac{dE_n}{dt} + j_n \quad (6)$$

From equation (6), which states that the sum of the displacement and particle currents is the same in both layers,

$$t = \int_{V_{FB}^i}^{V_{FB}^f} \frac{\epsilon_o dE_o - \epsilon_n dE_n}{j_n - j_o} \quad (7)$$

When equation (2) is differentiated, combined with equation (3), and substituted into equation (7), one obtains

$$t = \frac{\epsilon_n}{x_n} \int_{V_{FB}^i}^{V_{FB}^f} - \frac{(dV_{FB})}{j_n - j_o} \quad (8)$$

Equation (8) gives the time to change from V_{FB}^i , the initial flatband voltage to V_{FB}^f , the final flatband voltage. The result holds for any two-layer insulator system on a nondegenerate semiconductor. If the denominator is changed to $j_n + j_o$, the equation also holds for discharging (removing stored charges). The value of V_{FB} as a function of time can be determined if equation (8) is integrated using equations for j_o and j_n and the proper limits.

The effects of radiation enter into equation (8) through the current density terms, j_n and j_o . It is assumed that at sufficiently high dose rates the

generation of charge carriers will depend primarily upon the radiation dose instead of bulk generation rates. In such a case, the net carrier density will not depend on applied field. This will give rise to a form of ohmic conduction across the oxide and nitride layers.

Net carrier density, considering recombination, and under irradiation is given by:

$$n = g\tau \text{ and } g = k\dot{R} \quad (9)$$

where g is the electron-hole pair generation rate and τ the effective (and constant) lifetime. In this case, g is assumed proportional by a constant k to the dose rate \dot{R} in rds/s. For ohmic conduction

$$1/\rho = ne\mu = eg\tau\mu = ek\dot{R}\tau\mu \quad (10)$$

where $1/\rho$ is the conductivity in (A/V)-cm, μ the mobility in $\text{cm}^2/\text{V-s}$, and e the number of coulombs per carrier. The conductivity is proportional to dose rate \dot{R} and a lumped material constant $\alpha = ek\tau\mu$ giving

$$1/\rho = \alpha\dot{R} \quad (11)$$

To complete the development of current density, there is Ohm's law

$$j = E/\rho = \alpha\dot{R}E \quad (12)$$

where j is current density in A/cm² and E is the field in V/cm.

Assuming that the current density due to radiation is much larger than the normal current density, the current density due to radiation can be substituted into equation (8) as follows:

$$j_{nR} = \alpha_n \dot{R} E_n \quad (13)$$

$$j_{oR} = \alpha_o \dot{R} E_o \quad (14)$$

where the subscript R indicates current density due to radiation.

Substituting for E_n and E_o in equations (13) and (14) by using equations (4) and (5)

$$j_{nR} = \alpha_n \dot{R} \gamma \epsilon_o (V_{GS} + \beta V_{FB}) \tag{15}$$

$$j_{oR} = \alpha_o \dot{R} \gamma \epsilon_n (V_{GS} - V_{FB})$$

Substitution of equations (15) and (16) into (8) using the current densities due to radiation leads to

$$-BR = \int_{V_{FB}^i}^{V_{FB}^f} \frac{dV_{FB}}{AV_{GS} + V_{FB}} \tag{16}$$

where

$$B = (\alpha_n \epsilon_o \beta + \alpha_o \epsilon_n) \gamma X_n / \epsilon_n \tag{17}$$

$$R = \dot{R}t, \text{ the total dose, and} \tag{18}$$

$$A = (\alpha_n \epsilon_o - \alpha_o \epsilon_n) / (\alpha_n \epsilon_o \beta + \alpha_o \epsilon_n) \tag{19}$$

After integration and rearrangement, this results in

$$V_{FB} = V_{FB}^i \exp(-BR) + AV_{GS} [\exp(-BR) - 1] \tag{20}$$

This expression describes the change of V_{FB} as a combination of an exponential decay of stored charge and an exponential buildup of new charges at the interface due to an applied voltage V_{GS} .

Since the flatband voltage and threshold voltage can be related by

$$V_{FB} = V_T = V_{T0} \tag{21}$$

equation (20) can be rewritten as

$$V_T = V_{T0} + \left(V_T^i - V_{T0} \right) \exp(-BR) + AV_{GS} [\exp(-BR) - 1] \quad (22)$$

Changes were made to equation (22) for the purposes of this study. The term multiplied by the constant A was set equal to zero since the value of V_{GS} was at zero during the experimental tests except for determinations of the threshold voltage V_T and the stable threshold voltage V_{T0} by ΔV_T and ΔV_{TMAX}

$$\Delta V_T = \Delta V_{TMAX} [1 - \exp(-BR)] \quad (23)$$

where $\Delta V_T^i = 0$, and the terms ΔV_T and ΔV_{TMAX} represent the change in threshold voltage for a given dose of radiation R. ΔV_{TMAX} represents the maximum threshold voltage shift given an infinite radiation dosage. It corresponds to the stable threshold voltage V_{T0} . Equation (23) should fit the experimental data from an MNOS when change in threshold voltage versus radiation dosage is graphed.

Marraffino et al., (ref. 6) used equation (20) to fit data from three MNOS devices with different oxide thicknesses and nitride trap densities. In each case the empirically determined value of the constant B was found to be $8 \times 10^{-7} \text{ rds}^{-1}$ (ref. 6, pp. 18-19). The value of B was considered to be relatively invariant due to the relative invariance of the conductance properties of the different oxide layers in the three device types (ref. 6, p. 19).

READ-DISTURB

A final characteristic of the MOS which must be considered is the read-disturb effect.* Reading is the operation of applying a variable V_{GS} to an MNOS to determine its threshold voltage. Any externally applied field (V_{GS}) will tend to disturb the amount of stored charge in the nitride. To prevent read-disturb effects, the read pulse-width must be kept much less than the write or clear

*Preliminary Standards for MNOS Transistor Characteristics, to be published pp. 2-22, Produced by the IEEE MNOS Standardization Subgroup in 1974.

pulse-widths. A possible mechanism for the read-disturb effect is trap-assisted charge injection as described by Svensson (ref. 9).

An example of a shift in threshold voltage due to read-disturb effect can be seen in figure 10. The write pulse for this device was 100 ms at +15 V. The output can be seen to have decreased during the 10 ms read pulses. The output voltage is read across a 10 k Ω resistor and indicates the changes in source drain current. The output would have remained constant had there been no read-disturb effects.

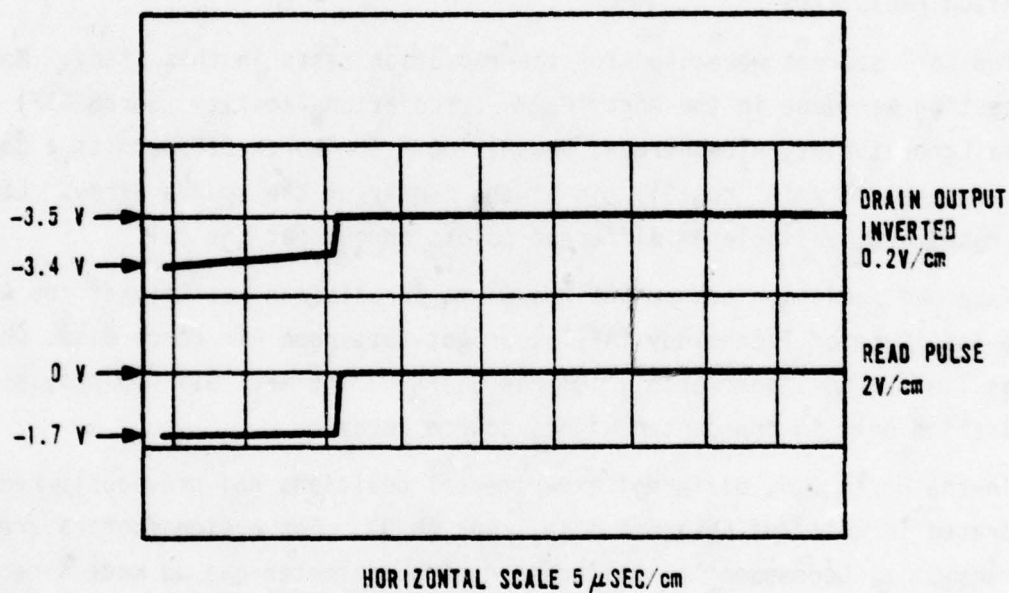


Figure 10. Read Disturb Effect on Threshold Voltage

9. Svensson, C. M. and K. I. Lundstrom, "Trap Assisted Charge Injection in MNOS Structures," Journal of Applied Physics, 44, pp. 4657-4663, October 1973.

SECTION III EQUIPMENT AND PROCEDURES

This chapter provides information on the radiation facilities used, the test devices and circuitry, and the experimental procedures used to obtain the data on the MNOS dosimeter. The second section of this chapter contains minimal information on the specific structure of the MNOS transistors because of restrictions on proprietary information. The final two sections, on experimental method and standardized testing procedure, are critical to the reproducibility of experimental results.

RADIATION FACILITIES

Two Co^{60} sources were used for the radiation tests in this study. Most of the testing was done in the North Gamma Irradiation Facility (North GIF) at Sandia Laboratories, Albuquerque, New Mexico. The North GIF permits a dose rate of nearly 6×10^4 rds(Si)/min at the center of the source array. Lower dose rates are available at different points throughout the cell.

A second radiation source was the Gamma Irradiation Facility at the Air Force Institute of Technology (AFIT), Wright-Patterson Air Force Base, Ohio. It was limited to a dose of 5×10^4 rds(Si)/hr. The AFIT GIT had provision for irradiation only in the center of its source array.

In the North GIF, different experimental positions had previously been calibrated in units of absorbed dose, rads (H_2O). Conversion factors are given for rads(Si). Consequently, calibration of a dosimeter can be made directly in rads by reference to the given exposure rate of the source.

MNOS TRANSISTORS

The MNOS transistors used in this study are test transistors which were fabricated along with several other circuits on a single silicon chip. The chips are packaged in 14-pin ceramic flat packs. However, leads were available only for the MNOS test transistors. Due to the restricted number of leads on a flat pack, there was some commonality of substrate, source, and gate leads. This permitted each of the six transistors on a chip to have a separate drain connection.

Standard MNOS production techniques were used to make the transistors. The dimensions given in figure 1 are approximately those of the transistors used in this experimental study. The experimental devices were prepared by Sandia Laboratories in August 1977.

Nonstepped gate MNOS transistors shown in figure 1 were the primary test devices. However, MNOS transistors with either a single or double stepped gate structure were also available on the MNOS device. None of these gate structures had diode protection and therefore required extra care in handling. Any discharge of static electricity into the unprotected gates could punch through the thin oxide, destroying the device.

TEST FIXTURES

Electrical contact to a selected transistor was provided by a test fixture, which permitted easy switching between the transistors on a single device or between different devices. The devices were held in flat-pack sockets attached to a 15 contact plug board. A device change, therefore, required only an exchange of plug boards. The plug boards mated with a socket in a small aluminum chassis box.

The chassis box had a series of eight single-pull double-throw (SPDT) switches that permitted selection of the transistor to be tested. One side of each switch was connected to ground and the other side was connected to either the gate or drain outputs on the chassis box. This design allowed a selected gate and drain to be connected to the test circuit while the other drains and gate were held at ground. In addition, a 1 M Ω resistor was connected in series with the gate output. The resistor served to protect the transistor being tested from excess current which might damage its gate. The chassis box also grounded all source and substrate leads.

THRESHOLD DETECTION CIRCUITY

A simple electronic circuit, shown in figure 11, was used to inject variable voltage and variable pulse-width signals into the gate of an MNOS under test. Roger Tallon of AFWL designed the original circuit, which had been used to test early MNOS devices for radiation hardness. The circuit was monitored at two places with an oscilloscope. The gate signal was monitored prior to the MNOS to determine voltage and pulse width, a second monitor point was the drain output of the MNOS. The drain was connected by a 10 k Ω precision resistor to the

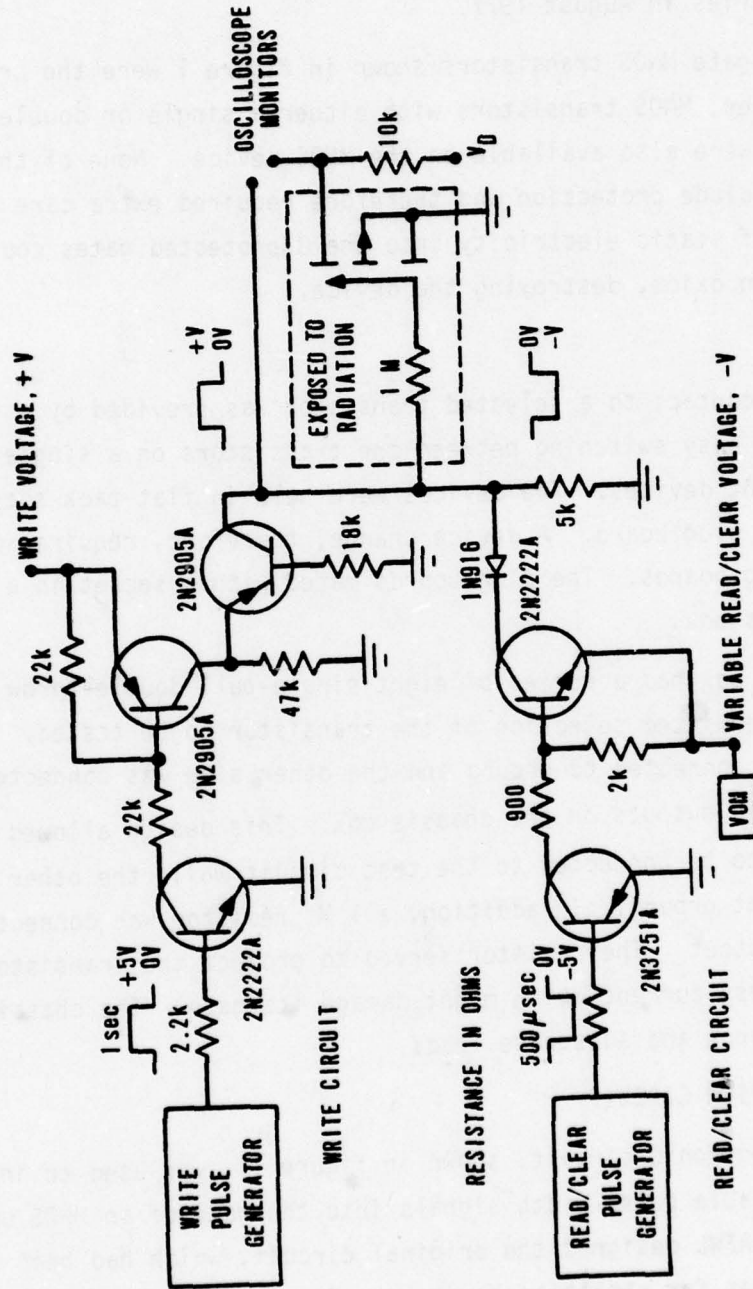


Figure 11. Threshold Voltage Measurement Circuit/MNOS Dosimeter System

drain power supply V_D . Any change in current through the resistor was seen on the scope as a change in voltage.

The circuit delivers either a positive (write) or a negative (read/clear) pulse into the gate of the transistor being tested. The amplitude of the pulse is varied through the use of variable power supplies for the read/clear and write circuits. Provision for varying the pulse width is provided by external pulse generators which trigger the test circuitry.

Read Pulse

The measurement of the amplitude of the read pulse is critical to the use of the circuit for reading the threshold of an MNOS. Best precision was obtained by reading the value of the read/clear power supply with a digital voltmeter. Although the full read/clear supply voltage does not appear at the gate, the reduction in voltage is nearly constant. It can be seen from figure 11 that most of the reduction is in the forward bias voltage of the diode which protects the read/clear circuit. For the circuit shown, this voltage reduction was 0.65 V. The values of threshold voltage reported in this paper all reflect the added 0.65 V. True threshold voltage as previously defined would equal the stated value minus 0.65 V.

The test circuit is connected to the test fixture with coaxial cable. The circuit is capable of driving 25 ft of 50 ohm cable with minimal signal loss. Only two cables are required between the circuit and test fixture. One cable carries the gate signal and the other carries the drain output signal.

OPERATION OF THE TEST CIRCUIT

The test circuit can be used for three operations on the MNOS being tested. First, it can be used to clear previously stored negative charge with a negative pulse. Second, it can be used to write the addition of negative stored charge with a positive pulse. Third, it can be used to read the threshold voltage with a negative pulse. The read/clear section of the circuit provides both of the necessary negative pulses. The two operations of reading and clearing only differ in pulse width and amplitude.

Clear

Clearing the MNOS being tested requires a large, -20 V, negative pulse of long duration, 1 s. The clear circuit is triggered by a -5 V pulse from an external pulse generator. Pulse width of the clear pulse is also determined

by the external pulse generator. The amplitude of the clear pulse is adjustable by selection of the power supply voltage to the read/clear circuit.

Figure 12 shows the results of a clear operation. The output at the drain is driven hard to ground since the MNOS is fully turned on. At the end of the pulse the output returns to V_D . The clear operation increases the magnitude of the threshold voltage and decreases the source-drain leakage current.

Write

Writing the MNOS is similar to clearing it. However, the polarities of the pulses are reversed. The write pulse and its trigger pulse are both positive. Amplitude and pulse width are adjusted the same as for the clear pulse.

The effect of a write pulse can be seen in figure 13. During the write pulse there is no change in output. The positive pulse tends to turn the MNOS off rather than on; however, at the end of the pulse the transistor is turned fully on and the drain output goes momentarily to ground. This is followed by an exponential return to V_D . The reaction is caused by the large number of trapped negative charges initially present in the nitride at the end of the write pulse. The MNOS is essentially fully turned on by its own internal fields. A large source-drain current flows until some of the charge leaks through the gate oxide. Several seconds after a saturation write pulse the leakage current returns to approximately 20 μ A.

Reading

The final operation for which the test circuit can be used is reading. The read pulse amplitude is continuously variable from near zero to -15 V. The power supply for the read/clear circuit has a fine voltage adjustment to permit output voltage changes of 0.01 V.

The required trigger for the read pulse is provided by the same pulse generator which triggers the circuit for clearing an MNOS. However, for read operations the pulse-width is reduced to the minimum, which will provide a clean output from the drain when threshold voltage is reached. Typically, a read pulse-width is more than two orders of magnitude less than a clear pulse-width.

For the MNOS tested in this experiment a read pulse-width of 500 μ s is used. A shorter, 200 μ s pulse is adequate when V_T is small in magnitude but not when V_T approaches 10 V. Figure 14 shows the effect of read pulse-width on an MNOS

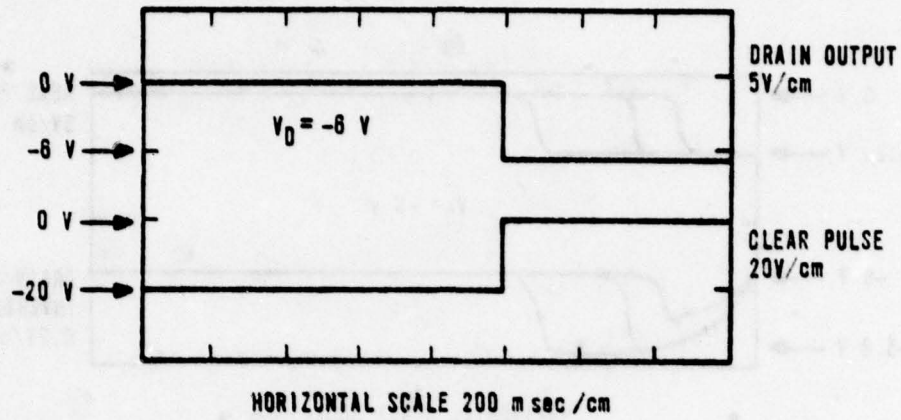


Figure 12. Generalized Response of an MNOS to a Clear Pulse

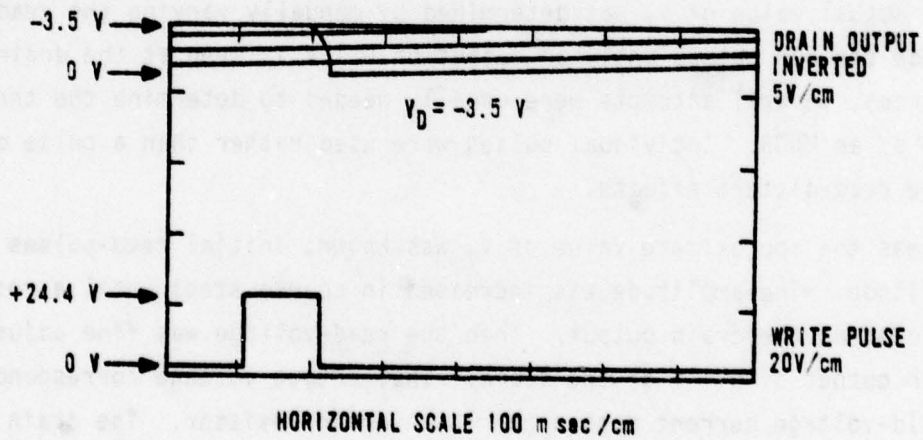


Figure 13. Generalized Response of an MNOS to a Write Pulse

device. The finite response time of the MNOS does not permit the shorter pulses to cause the same output as the longer pulse.

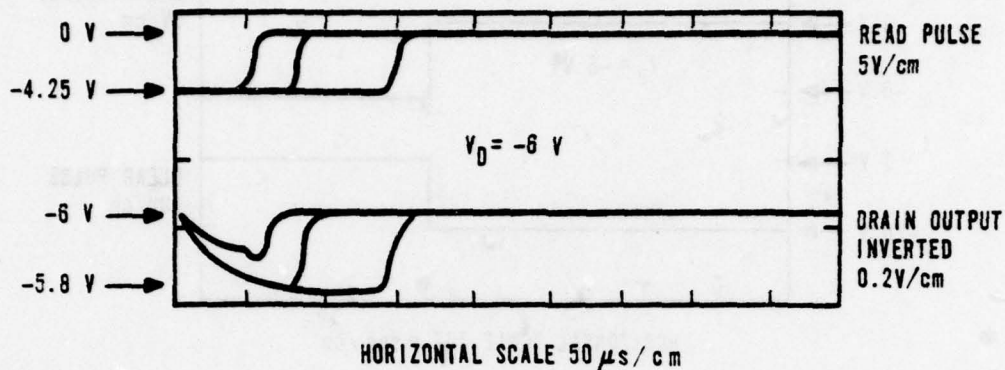


Figure 14. Generalized Response of an MNOS to Varied Read Pulse Widths.

EXPERIMENTAL METHOD

The actual value of V_T was determined by manually varying the read pulse amplitude between pulses until an output of 0.1 V is seen at the drain. With this circuit, several attempts were usually needed to determine the threshold voltage of an MNOS. Individual pulses were used rather than a pulse chain to minimize read-disturb effects.

Unless the approximate value of V_T was known, initial read-pulses were small in magnitude. The amplitude was increased in coarse steps until a response was first noted at the drain output. Then the read-voltage was fine adjusted to cause an output of 0.1 V at the drain. That output voltage corresponded to threshold-voltage current across the 10 k Ω drain resistor. The drain output was monitored in the AC mode of the oscilloscope. That mode eliminated a DC voltage signal caused by the slowly varying leakage current. Once the desired output was obtained, the voltage of the read/clear power supply was read from the voltmeter and recorded as the threshold voltage.

STANDARDIZED TESTING PROCEDURES

Time is a critical factor in any attempt to reproduce results with an MNOS. The fact that V_T changes with time means that any value of V_T applies only at

the instant at which it was determined. Therefore, any statement about threshold voltage must include information on the time history of the device.

Saturation

One convenient point for starting the time history of an MNOS is the saturate write point. The saturate write point has associated with it a fixed value of V_T for each MNOS transistor. Saturation is determined by a series of write, wait, read operations. Such a series is a write, a 15 s wait, and then a read. To accurately determine the threshold at the end of the 15 s period requires several read pulses during the waiting period. The last read pulse, which should be at threshold voltage, should come at the end of the 15 s period.

For the MNOS used in this study, five write pulses at 25 V with a pulse width of 1 s were used to insure saturation. Saturation has been reached when no further change in V_T occurs with additional write pulses. If desired, a single long write pulse can be used instead of the several short pulses.

Selected Threshold Voltage

A second point in time to start data on an MNOS occurs when the threshold voltage equals a set value. First a value of V_T is selected which is larger in magnitude than saturated V_T . Then the MNOS is written nearly to saturation. Finally, the device is read with pulses fixed at the selected threshold voltage amplitude. The drain output will initially be greater than 0.1 V when the output reaches 0.1 V. At that time the threshold voltage is equal to the selected threshold voltage.

SECTION IV

RESULTS

To demonstrate the feasibility of an MNOS dosimeter it was necessary to show that its response to radiation was reproducible. Once that was shown, data were required concerning minimum and maximum dose and the effect of dose rate. Experimental data were, therefore, taken on the effect of radiation and on the effect of time on the MNOS threshold voltage. Minimal data were taken on dose-rate effects since the MNOS is considered dose-rate independent. Tallon and Vail* indicated that under proper test conditions the MNOS responds only to total dose effects.

TIME DEPENDENCE

Initial tests of the variation of V_T with time indicated a logarithmic dependence. The curve in figure 8 shows the effects of time on V_T . The curve, on the semilog axes, is almost linear out to the last datum point at 47 hrs.

A linear least squares fit applied to V_T versus \log_{10} (time) yielded a correlation coefficient of 0.98. Consequently, data on V_T versus time was only taken for approximately 30 min on later MNOS transistors. The threshold voltage at later points in time was estimated by extrapolation of the initial data.

Figure 8 also shows the excellent reproducibility of the data for V_T versus time. The time history for the transistor was started from the saturation write point to insure a fixed starting value of threshold voltage.

The MNOS transistors used in this study respond slowly over time. This slow response is an asset in a device which is to be used as a dosimeter. Periods of hours are often required in experiments to achieve a large total dose.

*Tallon, R. W. and D. J. Vail, A Comparison of High Dose Rate Test Results on MNOS Transistors in E-Beam and Gamma Environments, Unpublished, Air Force Weapons Laboratory, Kirtland Air Force Base, New Mexico, December 1974

RADIATION AND TIME DEPENDENCE

The dependence of MNOS threshold voltage on the combined effects of radiation and time is shown in figure 15. The maximum dose shown, 4.3×10^6 rds(Si), required 3 hrs 45 min to accumulate. Radiation exposure was stopped at that time since the change in threshold voltage with further radiation had become minimal.

After the initial 4.3×10^6 rds(Si) exposure, the transistor was cleared and then written again to saturation. A second radiation exposure repeated the threshold voltage measurements out to 2 Mrds(Si). Further checks on reproducibility of data were made with two additional radiation exposures to 640 krds(Si) each. The data from the first exposure were seen to differ from that of the remaining radiation exposures. The difference was determined to be a systematic error of 0.14 V. The error was caused by failure to write the device fully into saturation prior to the start of the experiment.

After the constant 0.14 V error was subtracted from the first set of data, the standard deviation for the data was determined. Applying a single standard deviation to the data indicated a reproducibility of ± 0.01 V. This excellent reproducibility held for the remaining five MNOS transistors tested. The data showed such a high degree of precision, ± 0.01 V, that discrepant values were immediately apparent.

DOSIMETRY DATA

In order to use the MNOS as a dosimeter, the effect of radiation alone had separated from the previous data which included the effect of the time required for exposure to that calibrated radiation dose. Figure 16 shows the effect of radiation alone on the value of threshold voltage. The curve shows the change in threshold voltage versus calibrated dosage for an MNOS initially written to saturation. Primary radiation effect data for the curve were obtained from a single 4.3 Mrd irradiation. The first data points were then confirmed with a second irradiation to a calibrated dose of 640 krds. After the irradiation tests, a 22 min nonradiation test was made to determine the effects of time on the threshold voltage. The threshold voltage versus time curve was then extrapolated to provide data covering the time required to achieve the calibrated radiation dose. Then the time dependent threshold voltage data were subtracted from the radiation effect test data. Figure 16 is the result of the subtraction.

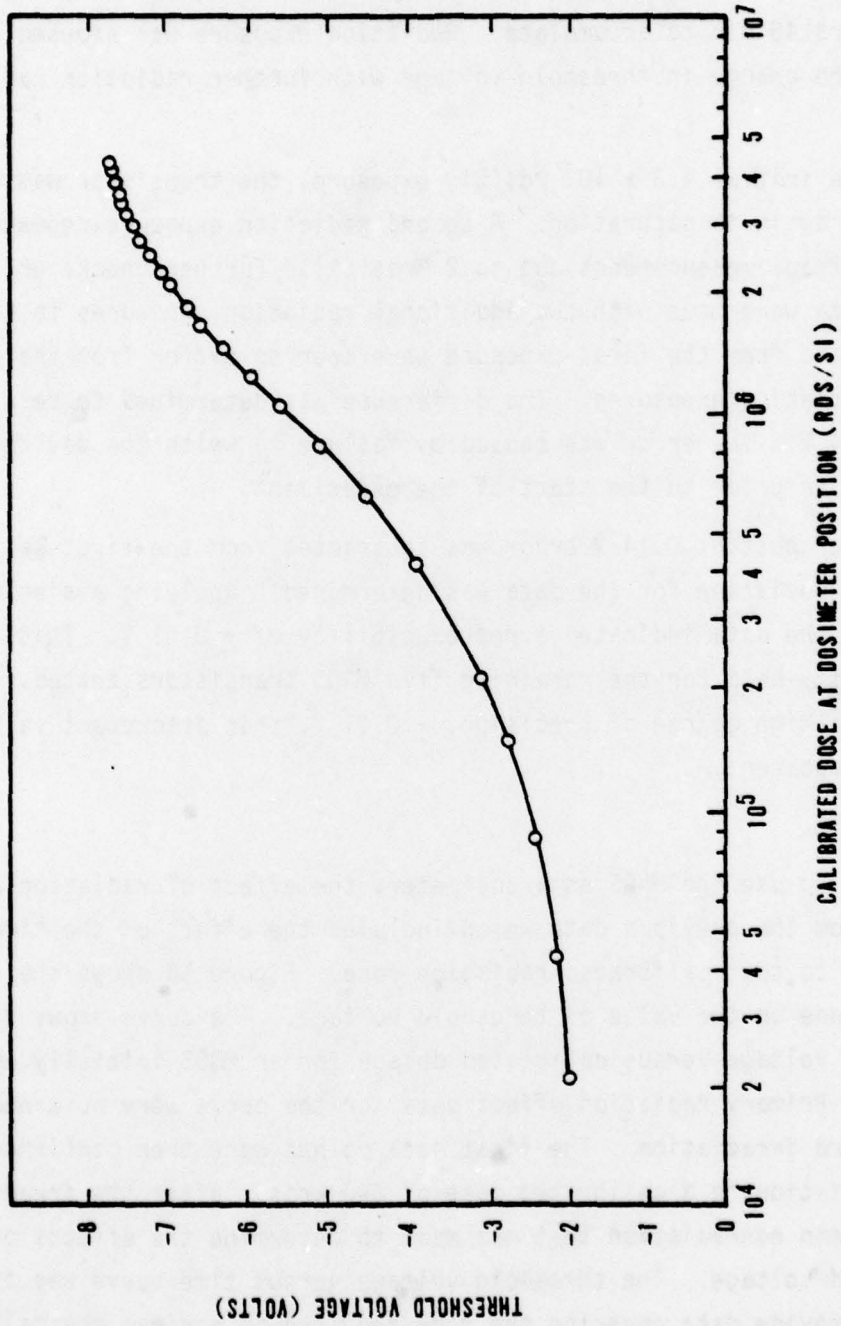


Figure 15. Threshold Voltage Versus Calibrated Dose in Rds(Si) at Dosimeter Position

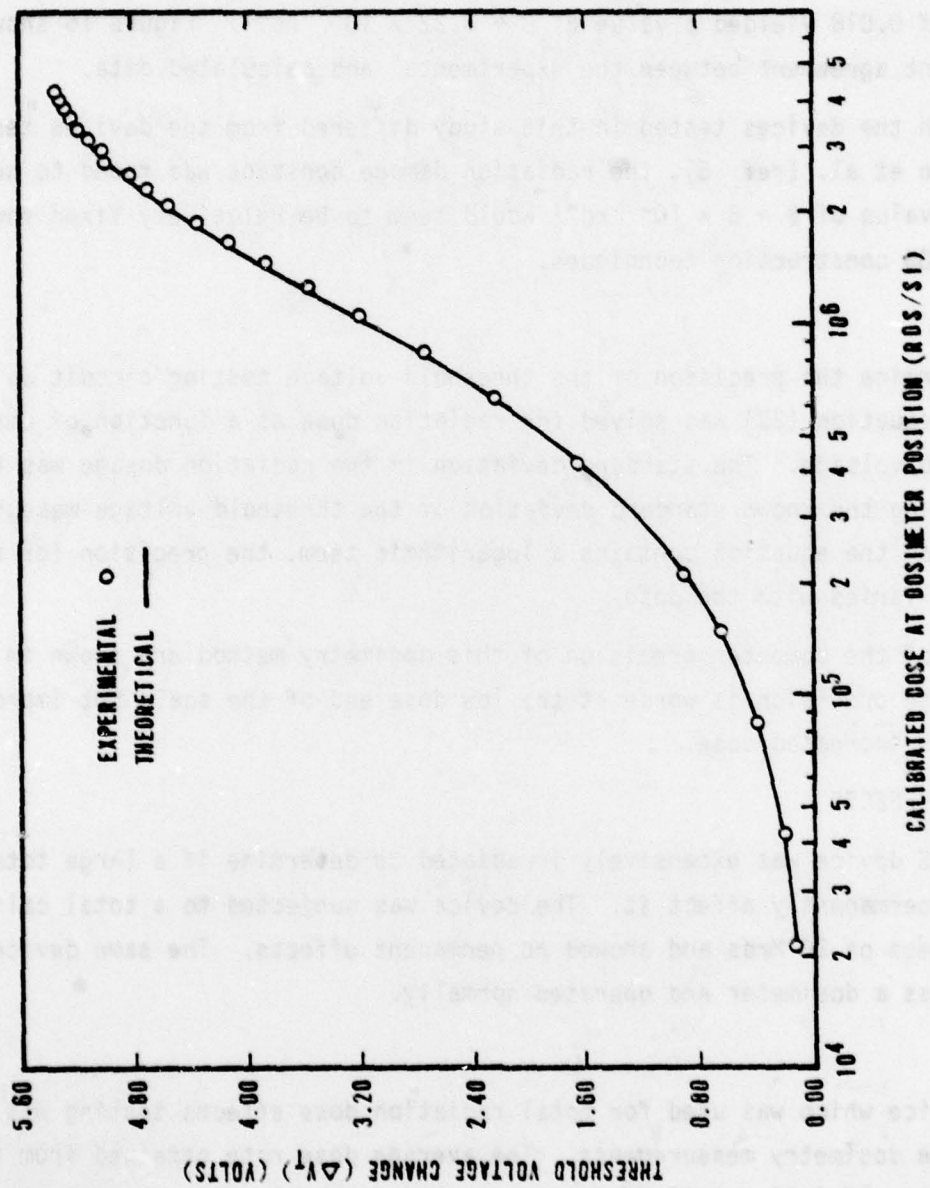


Figure 16. Change in Threshold Voltage Versus Calibrated Dose in Rds(Si) at Dosimeter Position

THEORETICAL CURVE FIT

Equation (23) was fitted to the data to determine the change in threshold voltage versus radiation shown in figure 16. A best value for the radiation effect constant B was found through the use of a nonlinear curve fitting computer program. With threshold voltage as the dependent variable a minimum RMS error of 0.018 yielded a value of $B = 8.22 \times 10^{-7} \text{ rd}^{-1}$. Figure 16 shows the excellent agreement between the experimental and calculated data.

Although the devices tested in this study differed from the devices tested by Mariffino et al. (ref. 6), the radiation damage constant was found to be the same. The value of $B = 8 \times 10^{-7} \text{ rd}^{-1}$ would seem to be relatively fixed for standard MNOS construction techniques.

PRECISION

To determine the precision of the threshold voltage testing circuit as a dosimeter, equation (23) was solved for radiation dose as a function of change in threshold voltage. The standard deviation in the radiation dosage was then computed using the known standard deviation of the threshold voltage measurements. Since the equation contains a logarithmic term, the precision for radiation dosage varies with the dose.

Values of the computer precision of this dosimetry method are shown in table 1. The precision is worse at the low dose end of the scale but improves rapidly with increased dose.

TOTAL DOSE EFFECTS

One MNOS device was extensively irradiated to determine if a large total dose would permanently affect it. The device was subjected to a total calibrated dose in excess of 20 Mrds and showed no permanent effects. The same device was used later as a dosimeter and operated normally.

DOSIMETRY

The device which was used for total radiation dose effects testing was later used to make dosimetry measurements. The average dose rate obtained from the MNOS dosimeter of 6.42 ± 0.08 krad/min compared favorably with the calculated dose of 6.5 krds/min. The results of the dosimetry are given in table 2.

A second dosimetry run was made with the same device in a much higher dose rate environment. The test fixture was placed in the center of the gamma cell

source array. An estimated dose for that position is 60 krd/min. The results of five dose calculations taken from two radiation exposures are given in table 3. The average dose obtained of 47.0 ± 0.2 krds indicates a relative precision of ± 0.4 percent.

Table 1
RELATIVE PRECISION OF MNOS DOSIMETER

Dose (rds)	Standard Deviation (krds)	Percent of Dose
21 k	± 2.3	11
150 k	± 2.5	2
213 k	± 2.6	1
1.9 M	± 10.4	0.5
4.0 M	± 61	1.5

Table 2
DOSE RATE CALCULATIONS AT LOW DOSE RATE

Time (min)	V_T (volts)	Time Data (volts)	ΔV_T (volts)	Dose (krads)	Dose Rate (Krds/min)
10	-2.12	-1.82	-0.30	63.9	6.39
20	-2.45	-1.88	-0.57	127	6.34
30	-2.74	-1.91	-0.83	196	6.53

Table 3
DOSE RATE CALCULATIONS AT HIGH DOSE RATE

Run	Time (min)	V_T (volts)	Calculated Time Data (volts)	ΔV_T (volts)	Dose (krds)	Dose Rate (krds/min)
1	6.26	-3.03	-1.79	-1.25	292	46.7
2	6.26	-3.04	-1.79	-1.26	292	46.7
1	10	-3.64	-1.82	-1.82	471	47.1
2	10	-3.65	-1.82	-1.83	471	47.1
1	16.22	-4.46	-1.86	-2.60	767	47.3

PERMANENT RADIATION DAMAGE

After minimal testing, those transistors which had stepped gate structures showed permanent radiation effects. The typical stepped gate transistor started with an 11 V difference between V_{TH} and V_{TL} . V_{TH} and V_{TL} are the threshold voltages in the saturated high-conduction state and the saturated low-conduction states, respectively. After a few megarads dose the value of V_{TH} had moved down to nearly the value of V_{TL} . The transistor no longer acted like an MNOS. Its characteristics were those of a fixed threshold MOS transistor.

A possible explanation of this is shown in figure 17. The thicker oxide on either side of the nitride layer can store charge in the same manner as an MOS transistor. The field placed on the gate and nitride layers eventually cannot overcome this excess charge. Consequently, the device no longer responds normally to write pulses. For this reason MNOS transistors with stepped gate structure cannot be used for dosimeters.

Charge Migration. A second permanent radiation effect was noted with these MNOS devices. When the devices were tested 2 weeks after their initial testing, their responses were not normal. Some would not operate at all with the 1 M Ω resistor in the gate circuit. For others, the response to a read pulse was a decrease in source/drain current. Such behavior was probably due to charge migration to the MNOS transistors from the remainder of the silicon chip.

The individual transistors occupied less than 1 percent of the total area of the chip. They were also the only circuits on the chip with connected leads. The stored charges in the MNOS transistors would have attracted any free charges which had been generated in the remainder of the large chip.

Such an effect has not been reported for discrete MNOS devices. For that reason, discrete devices are recommended for use in dosimeter applications.

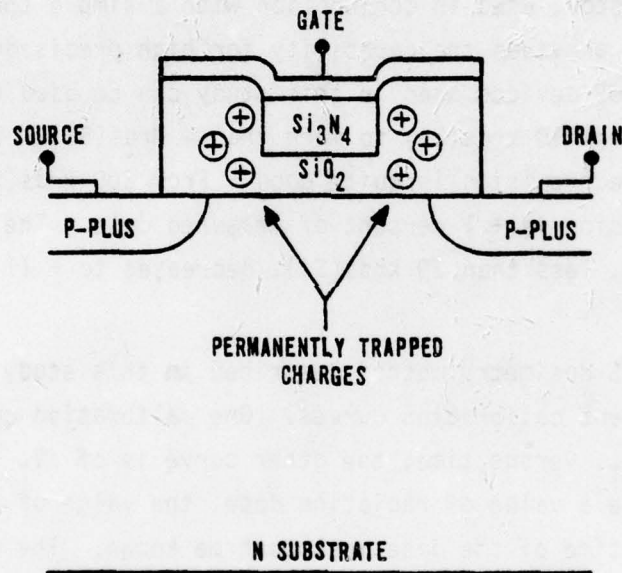


Figure 17. Stepped Gate MNOS Showing Permanently Trapped Charges

SECTION V

CONCLUSIONS AND RECOMMENDATIONS

This chapter presents the conclusions drawn concerning the use of an MNOS as a dosimeter and recommends further work to produce an MNOS dosimeter which is fully automatic. A possible method of automatic dosimetry using an MNOS is discussed.

CONCLUSIONS

An MNOS transistor, used in conjunction with a simple threshold voltage detection circuit, provides the capability for high precision, high dose level dosimetry. The MNOS devices used in this study can be used to measure exposure to doses ranging from 10 krds(Si) to more than 4 Mrds(Si). Within this dose range, the relative precision is quite good. From 200 krds(Si) to 4 Mrds(Si) the relative precision is ± 1 percent of measured dose. The relative precision at low dose levels, less than 20 krds(Si), decreases to ± 11 percent of measured dose.

Use of the MNOS dosimetry method described in this study requires determination of two different calibration curves. One calibration curve is of threshold voltage change, ΔV_T , versus time; the other curve is of ΔV_T versus radiation dose. To determine a value of radiation dose, the value of ΔV_T from saturation and the length of time of the dose must both be known. The value of ΔV_T due to the effects of time is first subtracted from the measured ΔV_T , and then the remaining ΔV_T is used to determine dose from the ΔV_T versus radiation dose curve.

MNOS transistors used for dosimetry should not have stepped-gate structures. The stepped-gate structure is like an MNOS gate with an MOS gate on either side. Under irradiation the two MOS gate sections degrade the performance of the MNOS. After sufficient dose, a few megarads(Si), the threshold voltage of the entire device is shifted to the low conduction state and can no longer be varied. Since this degradation is permanent, a stepped-gate MNOS should not be used for dosimetry purposes.

The permanent degradation by radiation of a stepped-gate MNOS also suggests problems in MNOS memory arrays. If stepped-gate devices are used, radiation

damage becomes permanent. It is possible that the radiation hardness of such an array would be limited to the hardness of a comparable MOS memory array.

Radiation effects in an MNOS which cause changes in threshold voltage can be described by the equation

$$\Delta V_T = \Delta V_{TMAX} [1 - \exp(-BR)] \quad (24)$$

where ΔV_T is the change in threshold voltage, ΔV_{TMAX} is the maximum change in threshold voltage, B is an experimentally determined constant (rad^{-1}), and R is the total dose in rads. The value for B determined for one of the devices in this study is 8.22×10^{-7} . This value corresponds to a value of 8×10^{-7} found by Marrifino, et al., (ref. 6, p. 18).

The use of MNOS devices which were part of a large MNOS test chip lead to permanent degradation of the MNOS devices. A probable cause for this damage is charge migration from the remainder of the large test chip to the MNOS transistors. Because of this effect, MNOS devices for dosimetry should be discrete transistors, if possible.

RECOMMENDATIONS

The final portion of this study involved an attempt to design a partially automatic dosimetry method. One requirement for full automation is an automatic threshold voltage detection circuit. Analog circuits exist for this task, but the inherent accuracy of a digital circuit is desired.

The block diagram of a suggested circuit is shown in figure 18. A circuit using that block diagram was breadboarded and given very limited testing. It was not always able to reproduce measurements to 0.01 V, and there was insufficient time to fully study the circuit. Much further work is needed to determine best design and test such a circuit for precision of measurement.

Further study is also recommended into the use of the MNOS dosimeter in other radiation environments. There is evidence that the MNOS is relatively insensitive to neutron effects (ref. 10). An MNOS dosimeter might therefore be able to measure gamma radiation in a reactor environment.

A final step in the development of an MNOS dosimeter would be to couple an automatic threshold voltage read to a small microprocessor. The microprocessor

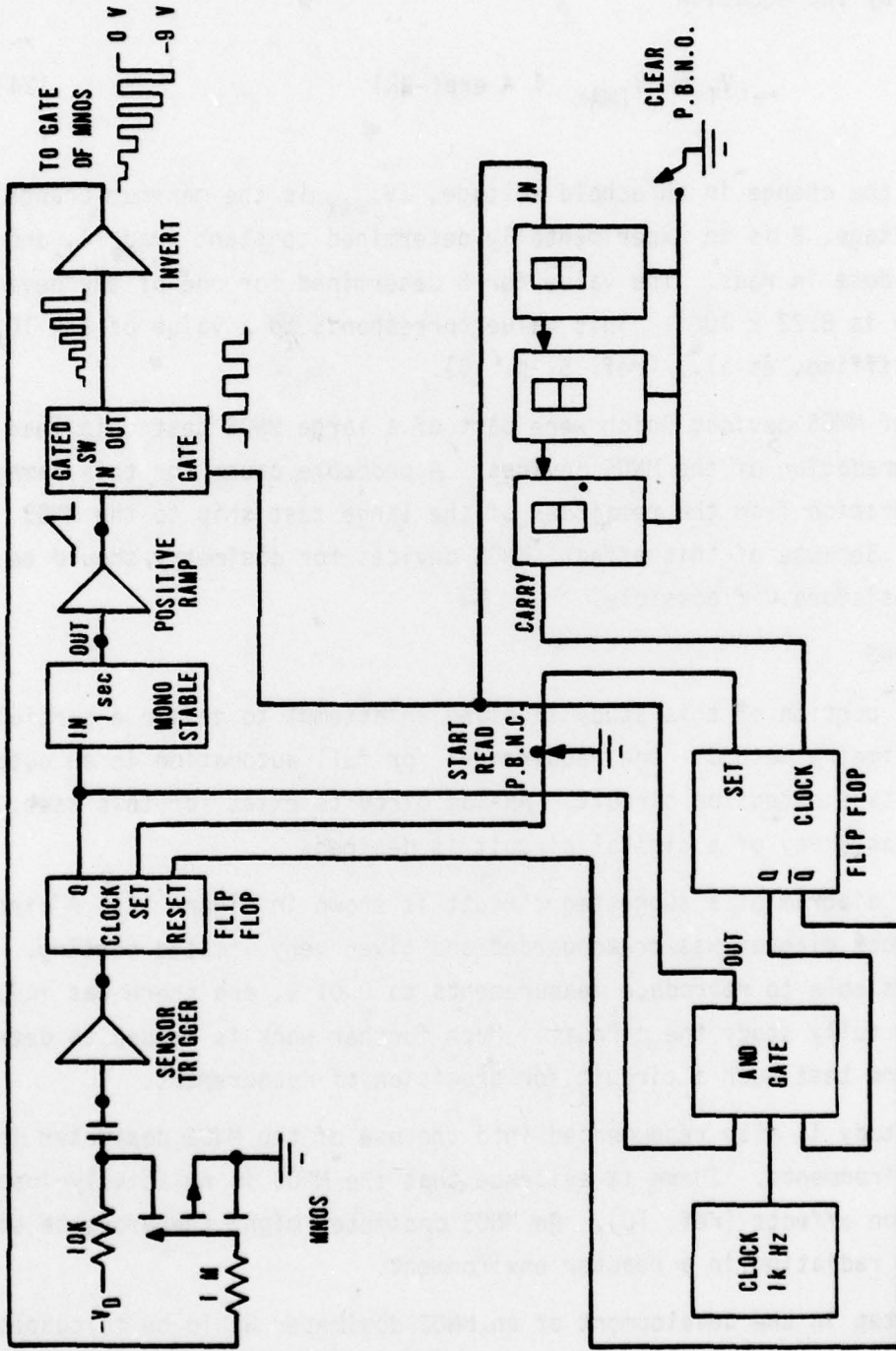


Figure 18. Block Diagram of Automatic Threshold Voltage Measurement Circuit

could store the data on threshold voltage versus dose and threshold voltage versus time, monitor the dosimetry runs, and provide an automatic digital read-out of dose.

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