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MOSFET DETECTOR EVALUATION

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Summary

Metal-oxide-semiconductor devices have been evaluated as low-energy (250 eV to 50 keV) x-ray dosimeters. They can be used to measure dosages as low as 1 rad (SiO_2) to as high as 10^5 rad (SiO_2). Their small size and basic simplicity make it possible to form arrays of dosimeters for x-ray imaging. When compared to thermoluminescent dosimeters (TLD's), photographic film, and thermopiles, MOSFET dosimeters offer distinct advantages in terms of their small size, their sensitivity to photon energies below 10 keV, and their adaptability to an electrical readout system.

Introduction

The effect of radiation on metal-oxide-semiconductor devices has been discussed at length during the past few years. To a first approximation, the behavior of the devices follows predictions based on a model developed for MOS devices.¹ Recently the primary effort has been on radiation hardening. Experiments have been conducted to discover processing steps that will make the devices less sensitive to ionizing radiation.²

Anyone working with radiation detectors cannot help but study the MOS radiation sensitivity work to see if any possibility exists for using MOS devices as dosimeters. Any substance will undergo some change if it is exposed to enough radiation. One must determine if such changes are reproducible and easily measured.

We have been using MOS devices as dosimeters for several years.³ Much experimental data has been accumulated that should be useful in evaluating them as dosimeters. Both MOS capacitors (MOSC's) and MOS field-effect transistors (MOSFET's) have been used.

The most useful application has been in the measurement of low-energy x-rays. These measurements are especially difficult for three reasons. First, the spectrum must be known fairly accurately since the detector absorption coefficient varies rapidly at low energies. Secondly, any container material covering the detector will attenuate the low-energy incident photons. Finally, the exposure rates are very high and cannot be handled by most dosimeters. With MOS dosimeters, only the first consideration is a problem. That is, the spectrum of the incident energy must be known in order to interpret the signal on the dosimeter. The devices have a very low energy window, since the metal electrode covering the dosimeter can be as thin as 500 Å. They can withstand exposures as high as 10^5 rad with no problem.

This paper begins with a brief review of the physical considerations governing the radiation effect in MOS devices. Both MOSC's and MOSFET's are dealt with. Several experiments are described where both high- and low-level dosages were measured. A special amplifier

was designed for the low-level measurements. A MOSFET array suitable for x-ray imaging is described. Finally, the MOS dosimeter is compared with TLD's, film, and thermopiles, the three dosimeters that are used in similar situations.

Review of the MOS Radiation Effect

The cross section of the radiation-sensitive region of an MOS device is shown in Fig. 1. This region is the SiO_2 dielectric of an MOSC or the gate oxide of a MOSFET. We will be examining two oxide thicknesses: 5000 Å for the case of an MOSC and 1500 Å for the case

Fig. 1. Cross section of an MOS device. The space-charge region builds to a saturation value given by the above equation.

*Work performed under the auspices of the U.S. Atomic Energy Commission.

of a MOSFET. In either case, the radiation effect is the same. That is, ionizing radiation causes a positive charge to be stored in the oxide. For the case of the MOSC, the value monitored before and after radiation is the flatband voltage V_{fb} . For the MOSFET, the turn-on voltage V_T is measured.

It can be shown that when an MOS device is irradiated a space-charge region of positive charge will build to a final thickness given by

$$d = \left(\frac{2\epsilon_0 V_g}{q N_t} \right)^{1/2} \quad (1)$$

where

d = thickness of the space-charge region

V_g = bias during irradiation, and

N_t = density of the positive charge in the space-charge region.

For a bias during irradiation of 10 V, and an assumed value for $N_t = 10^{18} \text{ cm}^{-3}$, the thickness of the space-charge region given in Eq. (1) has the value of 657 Å. This charge is permanent, and it can be measured long after the exposure. An experimental measurement of the turn-on voltage vs the energy absorbed in the SiO_2 dielectric is shown in Fig. 2. This curve must be determined experimentally because the values for N_t (the hole trap density) and the trapping efficiency are unknown and are process sensitive.

Fig. 2. General appearance of the turn-on voltage increase as a function of the energy absorbed in the gate oxide. A saturation value is approached (given by the above equation).

For an MOSC with a 5000-Å-thick oxide and a 10-V bias, the electric field in the oxide is $2 \times 10^5 \text{ V/cm}$. For a MOSFET with a 1500-Å-thick oxide and a 10-V bias, the electric field in the oxide is $6.7 \times 10^5 \text{ V/cm}$. These high fields sweep out the electrons that are generated in the oxide by the ionizing radiation. The holes become trapped in the hole traps, given by N_t . For a positive bias during radiation, the space-charge region builds from the SiO_2 -Si boundary. For a negative bias during radiation, it builds from the Al- SiO_2 boundary.

Regardless of the oxide thickness, the final thickness of the space-charge region (d) as a function of the absorbed dosage (in rad) is the same. It can

be shown that for a bias during radiation of $+V_g$, an oxide thickness of x_0 , and a final space charge layer thickness of d , the saturation value of the turn-on voltage change is

$$\Delta V_T(\text{sat}) = -V_g \left(\frac{2x_0}{d} - 1 \right) \quad (2)$$

The saturation value of $\Delta V_T(\text{sat})$ is found by using the value d calculated from Eq. 1. For the MOSC with the 5000-Å-thick oxide, $\Delta V_T(\text{sat})$ is -142 V. For the MOSFET with a 1500-Å-thick oxide, $\Delta V_T(\text{sat})$ is -36 V. From these calculations, it would appear that the MOSC was a more sensitive dosimeter. However, we will see later that the MOSFET is more sensitive because of the readout scheme that is used.

High-Dosage Measurements

MOS devices have been used to measure absorbed dosages of $10^5 \text{ rad (SiO}_2\text{)}$. For these kinds of exposures, the turn-on voltage change in a MOSFET or, equivalently, the flatband voltage change in an MOSC, is large enough so that not much sophistication is required in the readout electronics. Figure 3(a)

Fig. 3(a). Turn-on voltage characteristics of a MOSFET irradiated with successive dosages of $10^4 \text{ rad (SiO}_2\text{)}$ each.

shows the turn-on voltage characteristics for a MOSFET following successive exposures to low-energy x-rays. The x-ray source in this experiment was a tungsten x-ray tube operated at 30 kV and 15 mA. The plot of ΔV_T vs rad (SiO_2) in Fig. 3(b) shows good linearity up to $0.2 \times 10^5 \text{ rad (SiO}_2\text{)}$. Above $0.2 \times 10^5 \text{ rad (SiO}_2\text{)}$, ΔV_T approaches the saturation value given by Eq. (2).

The solid curve in Fig. 3(b) was measured using an exposure dose rate of around 200 rad (SiO_2)/sec. Several experiments were conducted to determine if the detector had dose rate effects, that is, if the change in ΔV_T for a given absorbed dosage is a function of the rate at which the dosage was absorbed. For the high-dose-rate experiments, a pulsed electron beam was used as the source. This beam was 20 nsec long, it had an average electron energy of 350 keV, and it resulted in a dose rate in the SiO_2 of 10^{12} rad/sec . Typical results of these pulsed measurements are shown in Fig. 3(b). There is fairly good agreement in detector sensitivity when a bias of +10 V is used during irradiation. For irradiation at zero bias, the pulsed source gives a higher signal than the low-dose-rate source. It is likely that this is caused by the

Fig. 3(b). Radiation sensitivity of a MOSFET irradiated at -10 V and 0 V gate bias.

diffusion of electrons out of the oxide, as has been observed by others.⁴

Low-Dosage Measurements

As was mentioned above, the saturation value of the flatband voltage change for an MOSC with a 5000-Å-thick oxide and a -10-V bias is -142 V. The saturation value of the turn-on voltage change of a MOSFET with a 1500-Å-thick gate oxide and a -10-V bias is -36 V. This implies that the MOSC is more sensitive than the MOSFET as a dosimeter by about a factor of 4. However, for the MOSC, the flatband voltage is measured by determining the capacitance as a function of voltage. With our measurement procedure, the smallest change in flatband voltage we can measure on the capacitance curve is 0.25 V. On the other hand, a change in turn-on voltage as small as 0.1 mV can be measured on a MOSFET. This is an increase in readout sensitivity of 2500 times.

The circuit used with the MOSFET to make low-dosage measurements follows earlier work by Pech and Holmes-Siedle.⁵ A schematic diagram is shown in Fig. 4. In this circuit, called a MOSIMETER, it is important that the constant-current source, the constant-voltage source, and the amplifier all be designed not to drift. Any drift will give an output signal that cannot be distinguished from the radiation-induced signal. Notice that the MOSFET is exposed under a negative gate bias. This makes the device less sensitive to radiation. However, the sensitive readout obtainable with this circuit more than compensates for the loss in detector sensitivity.

Before every exposure, the instrument is zeroed so that the voltage at point A is zero. Under this condition, there will be no current in the output meter. The MOSFET is then exposed to a source of radiation. The radiation causes an increase in the turn-on voltage of the MOSFET, which in turn causes the voltage at point A to decrease by the same amount. This voltage decrease is amplified and measured as a current in the output meter. An actual experiment with this circuit for an amplifier gain of 10 and a load resistor of 52.9 kΩ is shown in Fig. 5.

Fig. 4. MOSIMETER circuit used to measure small changes in MOSFET turn-on voltages caused by ionizing radiation.

Fig. 5. Results of an experiment using the MOSIMETER circuit shown in Fig. 4 with an amplifier gain of 10 and a load resistor of 52.9 kΩ.

Another MOSFET was built using an amplifier gain of 100 and a load resistor of 6.91 k Ω . We can calculate what is the smallest dosage that can be detected with a MOSFET in this new circuit. Assume that a current change in the output meter of 2 μ A can be detected. From the data in Fig. 5 we can determine that the MOSFET sensitivity is 7.94×10^{-3} rad/V. The 2 μ A current in the output meter of the new circuit corresponds to a turn-on voltage change of 1.38×10^{-3} V. Thus the smallest dosage measurable with this new MOSFET is approximately 1 rad (SiO_2).

To find out what are the minimum number of ergs/cm² that can be measured at various energies, we must use the absorption coefficient of SiO_2 . Also, the attenuation of a 1000-Å-layer of aluminum over the SiO_2 will be accounted for at the low energies. The number of ergs/cm² required to deposit 1 rad in SiO_2 are calculated from

$$1 \text{ rad}(\text{SiO}_2) = \frac{I_0}{100} \frac{(1 - e^{-\mu t})}{\mu t}$$

where

$$I_0 = \text{erg/cm}^2 \text{ incident,}$$

μ/ρ = mass absorption coefficient of SiO_2 , and

t = oxide thickness of 1500 Å.

The results of the calculations are shown in Table I.

TABLE I.

Minimum detectable fluence with a MOSFET dosimeter.

Photon energy (keV)	Fluence (erg/cm ²)
0.25	1.6×10^{-2}
1	5.4×10^{-2}
2	5.5×10^{-2}
5	3.1×10^{-1}
10	2.0
20	2.0×10
30	7.7×10
40	1.9×10^2
50	3.8×10^2

General MOSFET Dosimeter Characteristics

It is well known that the radiation tolerance of MOS devices depends on the processing used to make them. However, since they are very small, many can be made on the same wafer, where they will all undergo the same processing cycle. To verify this, several MOSFET's were selected from the same wafer and exposed to a pulse of electrons. The exposure was sufficient to change the turn-on voltage by 0.5 V. This voltage could be measured to within ± 0.005 V. They were exposed in groups of six. The variation of the turn-on voltage change among MOSFET's in the same group of six was within $\pm 3\%$. Supposedly, one could calibrate one

device on a wafer and then use all the rest as dosimeters.

The small size of the MOS devices allows one to make an x-ray imaging detector. Such an array is shown in Fig. 6(a). In this array there are 100 MOSFET's on

Fig. 6(a). Photograph of a 10x10 MOSFET array used for x-ray imaging.

a single silicon chip. The gates are tied to the vertical conductors and are accessible across the top of the array. The drains of the MOSFET's are connected to the horizontal rows of conductors. All of the source terminals are shorted to the substrate. Any individual MOSFET can be read out by selecting the appropriate gate and drain terminal. Figure 6(b) shows a close-up

Fig. 6(b). Close-up of MOSFET array. The gate regions are spaced 0.05 in. from each other. The gate and drain electrodes are accessible from the sides of the array. The sources are shorted to the substrate.

of the array. The gates of the MOSFET's, which are the sensitive regions, are spaced 0.05 in. apart. The drain conductors pass under the gate conductors by way of a p-diffusion. This array was used to map the cross-sectional intensity of an x-ray beam.

Once a MOSFET is exposed to radiation, the turn-on voltage is permanently changed to a more negative

value. These MOSFET's can be reused by annealing out the oxide charge at 400°C. Their radiation sensitivity after annealing is about 5% lower than it was before annealing. It is usually less bothersome to use a new MOSFET following an accumulated exposure of around 10^5 rad than to anneal and reuse the same device.

Equation (2) shows that the saturation value of the turn-on voltage change is a function of the gate bias during irradiation. This relationship has prompted us to try and use these detectors to get a time-resolved measurement of a short pulse of x-rays. The idea is to successively turn on the gate bias on several MOSFET's at increasing times during the pulse. Each MOSFET will record a signal that is related to the rads absorbed during the time when its bias is on. The results of some initial experiments have been published.⁶ Several other experiments are under way.

There are two difficult problems with the MOSFET scheme for time-resolved detection. The first is the requirement to supply fast rise-time pulses to the gates of the MOSFET's. Usually one is looking at pulse widths of less than 100 nsec, and the bias pulse to the MOSFET's must have a rise time of less than 1 nsec. The second difficulty is the need to keep any induced voltage from EMP effects away from the gates of the MOSFET's during the radiation pulse. We are currently working on these two problems and have obtained encouraging results using a 20-nsec pulse of high-energy electrons as the radiation source.

Dosimeter Comparison

It is instructive to compare the sensitivity and other characteristics of the MOSFET dosimeters with other, more conventional dosimeters. Three of these are thermoluminescent dosimeters, photographic film, and thermopiles.

Thermoluminescent dosimeters are used to measure photon energies above 10 keV.⁷ These devices are usually larger than 1 mm on a side. They are read out by observing their light emission upon warming. The lowest dosage that one can easily detect is 10 mR. If this dosage is converted to rad (SiO_2), it will be seen that TLD's are at least 10 times more sensitive than MOSFET's for photon energies above 10 keV. The advantage of the MOSFET dosimeters is that they work well below 10 keV, they can be made into closely spaced arrays, and they can be read out electrically.

The spatial resolution of photographic film cannot be matched by any other dosimeter. Also, its sensitivity is very close to the MOSFET sensitivity shown in Table I for energies above 10 keV. There is not much

available data below 10 keV. The disadvantage of photographic film as compared to the MOSFET's is that film is sensitive to light and must be kept sealed until it is developed.

Thermopiles can be conveniently read out electrically. However, calculations show that a 25-junction thermopile with 0.25-mil-thick gold absorbers would require around 10^4 erg/cm² of 10-keV photons to give a 1 mV signal. This flux is four orders of magnitude higher than required by the MOSFET dosimeters. Also, the spatial resolution of thermopiles is poor because of their large size.

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