A COMPARISON OF IONIZING RADIATION DAMAGE IN MOSFETS FROM COBALT-60 GAMMA RAYS, 0.5 TO 22 MEV PROTONS AND 1 TO 7 MEV ELECTRONS


Abstract

Non-radiation hardened P-channel and N-channel MOS transistors were irradiated with Co-60 gamma rays, 0.5 to 22 MeV protons, and 1 to 7 MeV electrons to determine the correlation between the gamma rays and the charged particles. Comparison of electrons to Co-60 showed that for equal absorbed doses, the damage produced was equivalent for all bias conditions. Under zero gate bias conditions, 2 to 22 MeV protons also produced damage in the test devices that was equivalent to Co-60. However, under bias conditions for high drain-source currents, the damage for protons below 22 MeV was always less than Co-60 (the lower the proton energy, the less the damage). The 0.5 MeV proton data showed poor correlation with Co-60 results. No dose-rate dependence was observed in the data. We conclude that, for the silicon MOS devices tested, the radiation damage produced by Co-60 provided a worst case simulation of high energy electron or proton damage.

Introduction

For years, investigators performing radiation tests on MOS components destined for use in space systems have relied primarily on Co-60 generated gamma rays to simulate the natural space radiation environment. A possible problem with this simulation method is that the natural space radiation environment consists mainly of high energy protons and electrons, and not Co-60 gamma rays. As a result, some scientists doubted that the radiation effects produced by laboratory gamma rays in MOS devices were equivalent to those produced by protons or electrons. Attempts to resolve this problem in the past have produced mixed results [1-4]. The Air Force Weapons Laboratory (AFWL) is conducting in-house research to help answer this question; this paper presents results of the first phase of this effort.

Test Procedures

The objective of this investigation was to measure the radiation-induced failure responses of discrete MOSFETs when exposed to gamma rays and high energy protons and electrons; then, from the results, determine the existing correlation between the gamma rays and the charged particles.

To accomplish this task, non-radiation hardened Intersil 3N161 P-channel and 3N171 N-channel discrete MOSFETs (from single manufacturing runs) were delidded and irradiated head-on with Co-60 gamma rays, 0.5 to 22 MeV protons, and 1 to 7 MeV electrons. After exposure to specified levels of radiation (under various gate and drain-source bias conditions), the transistors' I-V characteristics were measured and recorded "in situ", and the gate threshold voltages were then computed using ASTM techniques. The samples remained in the test-cells (with the radiation removed) during the characterizations. Turn-around time between exposures and device measurements was maintained at approximately 30 seconds or less. The changes in the gate-threshold voltage (Vth) for the three environments were then plotted as a function of ionized dose in rad(Si). From the results, the correlations between Co-60, protons, and electrons were determined.

The test facilities used in the above irradiations were the AFWL's 5-KCi Co-60 source for the gamma rays, the Los Alamos National Laboratory's (LANL) Tandem Van de Graaff Accelerator for protons, and the White Sands Missile Range Linear Accelerator (LINAC) for electrons. The AFWL Co-60 source was selected because it was a calibrated source (traceable to the National Bureau of Standards) and had a large test cell built to minimize low-energy scattering photons and electrons. The LANL accelerator was chosen because it could provide the desired range of mono-energetic protons (0.5 to 26 MeV) at a continuous and very stable low beam current (1 to 10 nA). White Sands' LINAC was chosen because it could deliver the desired electron beam into a specially built vacuum test chamber attached to the beam exit port.

Co-60 exposures were performed in local atmospheric conditions with radiation doses calculated from monthly dose-rate computations derived from calibrated ionization chambers and engineering calculations. The test devices were exposed to Co-60 dose-rates ranging from 13 to 37 rad(Si)/sec.

Proton irradiations were performed in an evacuated test chamber (Figure 1). The chamber enclosed a specially designed Faraday cup, a 1/2-inch double collimator unit, and a rotating aluminum disk attached to a remote-controlled stepping motor. The Faraday cup (with a current integrator) was used to measure the proton beam current. Beam area was defined, and held constant, by the collimators, and test samples affixed to the disk were rotated into the beam. To ensure accuracy, beam uniformity was monitored before each test cycle by irradiating a piece of cobalt dosimeter glass. Also, beam current was monitored through open slots on the test wheel before and after each test sample exposure. Finally (but most importantly), to eliminate the effects of secondary electrons, the second collimator and the Faraday cup were maintained at a positive potential with respect to the target wheel. These features, along with a remote-controlled beam-stop, allowed an accurate measurement of beam current, beam area, and beam exposure time. From these measurements, the proton fluence and the ionizing total dose (with the use of stopping power tables [5]) were determined. Dose-rate levels for the proton tests were maintained between 1 and 2 • 10^-6 rad(Si)/sec. A few special tests at other levels were conducted to investigate dose-rate dependencies.

Electron beam irradiations were also performed in an evacuated chamber (similar to the proton setup), but without a current integrator. The LINAC was a pulse mode machine, and the Faraday cup (with a current integrator), could not accurately measure the average beam current delivered by each pulse of radiation. Since the beam current was required to
determine the ionizing dose per pulse, it was necessary to incorporate the Faraday cup into a special RC circuit and then measure the peak voltage per pulse generated across this network during the radiation burst. With this measurement (and the pulse width of the burst and the capacitance of the RC network), the beam current per pulse was determined. Then, using stopping power tables [6] and the beam area, the dose per pulse and the dose rates were calculated. During the electron beam tests, the dose per pulse was maintained at 1 rad(Si) per 10 microseconds burst, delivered to the test devices at 60 pulses per second. The resulting dose-rate per pulse was \(1 \times 10^7\) rad(Si)/sec.

Test Results

Proton test results are summarized in Figures 2 through 9. Plots illustrate the comparison of ionizing total dose radiation from Co-60 gamma rays and selected high energy protons on the test samples, under various bias conditions. Test samples were irradiated straight-on, or at a zero degree angle of incidence. Sample sizes for the data plots ranged from 25 test devices for each Co-60 curve to 15 devices for each proton data bar.

The comparisons between Co-60 damage and the 2, 12, and 22 MeV proton damage, recorded with a Vga = 0 Volts on the test devices (Figures 2 and 3) show a direct correlation. That is, for equal absorbed doses, the Vth shifts produced by the Co-60 or by any of the three proton energies were equivalent. Similar results were obtained from 4, 8, and 16 MeV protons. Preliminary data on other MOS devices produced comparable findings [7].

Damage comparisons between Co-60 and the different energy protons, recorded under bias conditions with high drain-source currents, are presented in Figures 4 and 5. These plots show that the damage produced by the protons at energies below 22 MeV is less than Co-60. They also show the proton damage, when plotted in dose, is directly proportional with energy. That is, the higher energy protons were more damaging than the lower energy protons.

Comprehensive plots comparing the overall damage of Co-60 against protons with energies ranging from 2 to 22 MeV are shown in Figures 6 and 7. The Damage Sensitivity at \(\Delta Vth/Dose\) for Co-60 and the six different energy protons striking the biased test samples at a zero degree angle of incidence are plotted as a function of proton energy. These graphs were obtained by replotted the data like that presented in Figures 4 and 5 in log-log fashion and determining the slope \(\Delta Vth/Dose\) for each of the different radiations. The range in which the slopes were measured started at dose levels of a few Krad(Si) and continued out over the full (high dose) range. Over this range linear behavior in the data was observed, which resulted in straight line representations of the slopes. The numerical values of this parameter were then plotted in Figures 6 and 7 in Volts/Krad(Si) and labeled Damage Sensitivity. The resulting graphs show that the damage produced by the protons gradually and uniformly increases with energy until, at approximately 16 to 20 MeV, the proton induced damage begins to correlate directly with Co-60. These results (along with the plots in Figures 4 and 5) show that the proton damage on the test devices was strongly influenced by the electrical bias conditions, especially the field across the gate-substrate junction.

Figures 8 and 9 compare the damage results for 0.5 MeV protons and Co-60, for both hard-on bias and zero gate bias conditions. Note that the proton data does not track with Co-60 under any bias condition. These anomalous results can be attributed to large initial energy losses of the incoming protons as they travel through the silicon dioxide passivation (approximately 1.6 microns) and aluminum metallization (approximately 2.8 microns) layers of the test samples. Since the approximate range of 0.5 MeV protons is 5.6 microns in the metallization layers and 4.55 microns in the passivation layer, it is apparent that the proton energy spectrum is significantly degraded and peaks at less than 0.5 MeV in the 0.28-micron gate oxide. Further studies must be done to better understand the results of such a spectral degradation.

As a final proton-damage study, dose-rate tests were performed with 22 MeV protons. The dose-rate levels were \(1-2 \times 10^4\), \(1-2 \times 10^5\), and \(1-2 \times 10^6\) rad(Si)/sec. The results showed that the damage produced in the test samples was independent of dose rate. This was expected since the test devices were not radiation hardened and exhibited little or no annealing from the radiation damage. Moreover, these results agreed with previously published works [8,9], which showed no rate dependency in discrete IGFETs at the above low dose rates.

Damage due to 1, 3, 5, and 7 MeV electron irradiations versus Co-60, compared in Figures 10 through 13, are shown as changes in the gate Vth of the test devices as a function of electron energy and electron and Co-60 ionized total dose. The threshold voltage shifts are plotted for both hard-on and zero gate bias conditions. The damage produced by the various energy electrons (for equal absorbed doses) was equivalent to the Co-60 damage. This was true for all bias conditions tested.

Finally, in Figures 14 and 15 preliminary data are presented showing the effects of irradiating the N-channel test devices with 2 MeV protons or 5 MeV electrons at both 0 and 45 degree angles-of-incidence. The damage induced in the test samples from the 12 MeV protons was greater at 45 degrees than at 0 degrees. The electron damage at both angles was equivalent. That is, for equal absorbed doses, the 5 MeV electrons incident on the devices at 0 and 45 degrees produced the same Vth shifts. Similar results were obtained on the P-channel devices.

Discussion

Faraday cup dosimetry was chosen for use in the proton and the electron irradiations for its high sensitivity, accuracy, and adaptability. It has the ability to determine particle flux, fluence and dose from basic physics measurements. Unlike other types of dosimetry such as Thermoluminescent Detectors (TLDs), the Faraday cup does not have to be calibrated in each radiation environment against another dosimeter system. TLDs respond differently to different types of radiation [10]; as a result, before they can be used as dosimeters, they must be calibrated in each radiation specie. This secondary process only increases the probability of error. For this reason, TLDs were never used as the primary dosimeter in this effort. Calorimeters were also considered, but were rejected because of their lack of sensitivity and slow response times to low doses of radiation delivered in rapid and continuous pulses, as occurred in the electron-beam irradiations.
The results of the investigation were in partial agreement with previously published results [1,3]. The consensus involved the damage response data from low energy protons. All results showed that the damage per unit dose, produced by the protons in the MOS devices under bias, increased as the proton energy increased. Also, the damage in the biased parts from protons (below 10 MeV) was always less than that from Co-60. Finally, the damage in the biased devices was greater for 45 degree incidence protons than it was for 0 degrees. There was, however, disagreement in the electron-beam results. Results from references 1 and 3 showed that electrons between 1 and 7 MeV produced more damage per unit dose than Co-60. Data presented in this paper shows that the damage from 1 to 7 MeV electrons correlates directly with Co-60, regardless of the device bias. Possible explanations for this discrepancy may be the selection of test devices or differences in test procedures. In this effort, the test devices were non-hardened discrete MOSFETs, and the electron-beam irradiations were carried out in a vacuum using Faraday Cup dosimetry. In the previous efforts [1,3], the irradiations were carried out on Dual Complementary COS/MOS inverters (soft and hardened oxides) using TLDs, possibly under atmospheric conditions.

Results presented here are also in qualitative agreement with the analytical findings published by Oldham [11]. For example, the correlation between the electron and Co-60 irradiations was in accord with the Gamine Recombination Model, while the low energy proton results (below 4 MeV) agreed with the Columnar Recombination Model. Furthermore, the 4 to 22 MeV proton data, which fell within the transition region between the two models, is supported by the smooth, qualitative curves presented by Oldham.

Figures 14 and 15 present the initial results of a new phase of work to determine the effects of ionization and recombination on the same MOS devices under applied electrical fields when irradiated at different angles of incidence. Preliminary results show that for protons, the angle between the incident particle and the track of the incident particle had a major effect on the radiation damage produced in the test devices. Damage was greater at 45 degrees than at 0 degrees. Oldham and McGarrity [12] observed similar results for MOS capacitors irradiated with alpha particles. The damage produced by the electrons, however, showed no dependency on the angle between the incident particle and the gate oxide field; the radiation damage was the same at 0 and 45 degrees of incidence. An explanation for these results may be that, for proton irradiations, the ionization regions are localized around the tracks of the incident protons and, therefore, influenced by the oxide field lines. A field parallel to the tracks causes the electron hole pairs to move in the opposite directions along the track and increases the probability of recombination. The net result is a decreased radiation response. However, a field at an angle of 45 degrees with the tracks causes the electron hole pairs to be pulled in opposite directions, away from the track, thereby resulting in less recombination and greater radiation responses. For the electron-beam exposures, the ionization in a gate oxide is similar to that produced by Co-60. That is, the generated electron hole pairs are distributed in an isotropic manner throughout the oxide. The result is no change in the radiation damage for different field angles.

Conclusions

For the MOS devices tested, the radiation damage induced from Co-60 was always greater than, or equal to, the damage produced by 2 to 22 MeV protons or 1 to 7 MeV electrons under all bias conditions. The damage induced in the test devices from 1 to 7 MeV electrons correlated directly with Co-60, regardless of device bias. A direct correlation also existed for 2 to 22 MeV protons and Co-60, but only under zero bias or grounded conditions. Under bias conditions, however, the damage induced by the protons never exceeded that of Co-60, but varied directly with increasing beam energy and with the electric field across the gate-oxide. This confirms that proton damage in MOS devices is bias and energy dependent. Therefore, for the type of MOS devices tested, Co-60 irradiations are a reliable worst case simulation for the natural space radiation environment.

References

**Fig. 1. Proton Test Setup.**

**Fig. 2. PMOS Data. Protons versus Co-60. Change in Gate Vth as a function of Proton and Co-60 Ionized Dose for a Gate Vth of 0 Volts.**

**Fig. 3. NMOS Data. Protons versus Co-60. Change in Gate Vth as a function of Proton and Co-60 Ionized Dose for a Gate Vth of 0 Volts.**

**Fig. 4. PMOS Data. Protons versus Co-60. Change in Gate Vth as a function of Proton and Co-60 Ionized Dose for a Gate Vth of -5 Volts.**

**Fig. 5. NMOS Data. Protons versus Co-60. Change in Gate Vth as a function of Proton and Co-60 Ionized Dose for a Gate Vth of +5 Volts.**
**TEST DEVICE**
3N161 PMOS Transistor (Interst)

**TEST CONDITIONS**
Vgs: -5 Volts
Vds: 0 or -10 Volts

**DAMAGE SENSITIVITY (ΔVth/Dose) Volts/ rad(Si)**

CO-60

PROTONS (Incident Angle = 0°)

**PROTON ENERGY - MeV**

Fig. 6. PMOS Data. Comparison of Damage Sensitivity, ΔVth/Dose, between 2 to 22 MeV Protons and Co-60, for a Gate Vth of -5 Volts.

**TEST DEVICE**
3N171 NMOS Transistor (Interst)

**TEST CONDITIONS**
Vgs: +5 Volts
Vds: 0 or -10 Volts

**DAMAGE SENSITIVITY (ΔVth/Dose) Volts/ rad(Si)**

CO-60

PROTONS (Incident Angle = 0°)

**PROTON ENERGY - MeV**

Fig. 7. NMOS Data. Comparison of Damage Sensitivity, ΔVth/Dose, between 2 to 22 MeV Protons and Co-60, for a Gate Vth of +5 Volts.

**Test Devices**
3N161 PMOS Transistors (Interst)

**Pre-radiation Vth**
-2.15 to -2.40 Volts

**0.5 MeV Protons**
Vgs: +5 Volts
Vds: 0 Volts

**Co-60**
Vgs: +5 Volts

**Incident Angle = 0°**

**DOSE - rad(Si)**

Fig. 8. PMOS Data. 0.5 MeV Protons versus Co-60. Change in Gate Vth as a function of Proton and Co-60 Ionized Dose for a Gate Vth of 0 and -5 Volts.

**Test Devices**
3N171 NMOS Transistors (Interst)

**Pre-radiation Vth**
+1.95 to +1.65 Volts

**0.5 MeV Protons**
Vgs: +5 Volts
Vds: 0 Volts

**Co-60**
Vgs: +5 Volts

**Incident Angle = 0°**

**DOSE - rad(Si)**

Fig. 9. NMOS Data. 0.5 MeV Protons versus Co-60. Change in Gate Vth as a function of Proton and Co-60 Ionized Dose for a Gate Vth of 0 and +5 Volts.
Fig. 10. NMOS Data. 1.0 MeV Electrons versus Co-60. Change in Gate Vth as a function of Electron and Co-60 Ionized Dose for a Gate Vth of 0 and ±5 Volts.

Fig. 11. PMOS Data. 3.0 MeV Electrons versus Co-60. Change in Gate Vth as a function of Electron and Co-60 Ionized Dose for a Gate Vth of 0 and ±5 Volts.

Fig. 12. NMOS Data. 5.0 MeV Electrons versus Co-60. Change in Gate Vth as a function of Electron and Co-60 Ionized Dose for a Gate Vth of 0 and ±5 Volts.

Fig. 13. PMOS Data. 7.0 MeV Electrons versus Co-60. Change in Gate Vth as a function of Electron and Co-60 Ionized Dose for a Gate Vth of 0 and ±5 Volts.

Fig. 14. NMOS Data. Change in Gate Vth as a function of Dose and Proton Incident Angle for a Vth of +5 Volts.

Fig. 15. NMOS Data. Change in Gate Vth as a function of Dose and Electron Incident Angle for Vth of +5 Volts.