DOSE DEPENDENCE OF SINGLE EVENT UPSET RATE IN MOS dRAMS⁺

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The upset sensitivity of MOS dynamic RAMs has been found to decrease as a result of total dose irradiation, both for cobalt-60 gammas and MeV helium ions, up to the point where device failure is imminent. Device failure levels have been compared for cobalt-60 gammas, and MeV helium ions and protons. It has been found that in terms of rad(Si) necessary to cause device failure, cobalt-60 was more effective than protons which were more effective than helium ions.

INTRODUCTION

For a number of years, single event upset (SEU) experiments have shown that single energetic particles such as electrons¹, protons²⁻⁴, helium ions⁵⁻⁹, and heavier ions¹⁰⁻¹² can produce non-permanent changes in data patterns in integrated circuit random access memories. In the course of determining upset sensitivities, total damage is accumulated. The question arises whether the upset rate is changed by this total dose damage. If the SEU sensitivity does change with total dose, it may be difficult to obtain adequate statistical accuracy on the upset rate of an upset resistant device without changing the rate as a result of the measurement. The answer to this question is also important from an operational point of view. For example, the electronics in a satellite which passes through the earth's radiation belts will exhibit total dose degradation, mainly due to trapped electrons, and may be susceptible to SEU's, mainly due to trapped protons. As the total dose accumulates over time, the characteristics of individual device components will change, and these changes may alter the SEU upset sensitivity. It is important for a system such as this to know if the SEU sensitivity of a particular device is affected by total dose exposure.

This work reports on an investigation of the effect of total dose exposure on the sensitivity of metal-oxide-semiconductor (MOS) dynamic random access memories (dRAMs). MOS dRAMs have been chosen because they are known to be sensitive to SEU and a large amount of data has been published on these devices⁵⁻⁹. In the present experiment ⁴He ions and cobalt-60 gamma rays have been used to deposit total dose and ⁴He ions have been used to measure the SEU rate on 16K dRAMS from two manufacturers. Since the total dose degradation of these devices will depend on their operational mode, they were irradiated both powered and unpowered. In the former case approximately half the dose was delivered with all 0's stored in the dRAM and half with all 1's stored.

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EXPERIMENTAL SET-UP

The MOS dRAMS were tested in a microcomputer test system which has been previously described⁷⁻⁹. The devices were filled with either all 0's or all 1's and checked for changes. The devices were operated at specified voltage levels with a refresh period of about 1 millisecond. The devices were decapped just prior to the experiment. The 16K dRAMS are of the 4116 type manufactured by Texas Instruments (TI) and Motorola.

Total dose accumulation was accomplished in two ways: by exposure either to cobalt-60 gamma rays from a low flux gamma cell or to ions (protons or helium ions) from the NRL Microbeam.^{7,8} Dose rates were of the order of 50 rad(Si)/second for the helium ions and 0.7 rad(Si)/second for the gamma rays. The devices were exposed in steps such that device failure took place after 5 to 20 steps. The exposures were under powered and unpowered conditions with the powered devices exposed such that all 1's or all 0's were stored in the memory during alternate radiation exposures. In the case of the ion exposure, in some cases certain areas of the device were masked from the beam using a metal foil mask. The cobalt-60 exposures were performed with the caps taped onto the devices with the devices behind about 6 mm of aluminum for establishing approximate electronic equilibrium and to shield against low energy electrons. Thermoluminescent dosimeters were used to establish the dose rate. The ion exposures were performed in the vacuum of the microbeam facility with the caps removed. Doses were calculated from the energy of the beam, the ion stopping power, and from a measurement of the ion fluence. For the 3.3-MeV helium ions, 1 krad(Si) corresponds to a fluence of $7.9 \times 10^7/\text{cm}^2$. The microbeam facility includes provisions to accurately monitor the beam flux by measuring a fraction of the beam that is scattered by a thin foil.⁷ Uniformity of the beam over the area of the RAM die is better than 10% and the accuracy of the beam flux measurement is estimated to be about 10%.

Upsets were produced by either exposing the dRAM to an americium-241 alpha source (5.5-MeV energy, approximately .1 microcurie strength) in the case of the cobalt-60 irradiations or to 3.3-MeV helium ions in the case of the ion irradiations. The upset measurements were performed with fluences small compared with the fluences used for damage, so little total dose was deposited during these measurements.

Devices were tested until they were unable to retain a memory pattern of all 1's or all 0's. Some tests were performed after a fill with only one pattern was successful. In all cases, hard errors were checked for after each upset run and these were not included in the upset calculations. Error bars on the graphs to follow represent statistical standard deviations in the upset measurements.

Devices were also exposed unpowered. This was accomplished by first powering up the device and confirming that it was functional, powering-down, irradiating, and then repowering and confirming functionality. The device was then ready for an upset measurement.

DYNAMIC RAMS

Dynamic RAMS store information in MOS capacitors. Figure 1 is a schematic representation and cross-section of a dRAM memory cell. A "1" or a "0" is represented by an empty or full capacitor. The capacitor itself is in deep depletion and a gate allows charge to be stored in the capacitor by either filling this depletion region or potential well with minority carriers or emptying it. Since thermally generated minority carriers are always present, an empty well (a "1" in the normal convention) will always be filling with minority carriers and as such must be "refreshed" periodically (usually specified as within about a millisecond) to restore a stored "1". The process of reading a cell automatically refreshes the cell being read and all other cells in the same row, and so the refresh process usually consists of sequentially reading each row of the memory. Reading and writing are accomplished by selecting a particular cell via a word line thru a transistor gate and sensing or writing a cell via a bit line. As indicated in Figure 1 for the particular design of dRAM used in these experiments, the word lines are metal, the bit lines are diffused and the capacitors and transistor gates are formed with polysilicon on a p-type substrate to form n-channel MOS.

Figure 1. This shows a cross-section view of one memory cell of a DRAM together with a circuit diagram of the cell components.

Figure 2 is a schematic of the layout of the Texas Instruments 16K dRAMs used in this work. The memory cells are divided into two halves with one half, denoted normal, storing information in the standard way ("1" stored as an empty well), and the other half using the opposite convention and referred to as the inverted half. Sense amps in the center are connected to the memory cells and the dummy cells via the bit lines and are used to determine the state of an individual cell by comparing it with a pre-charged dummy cell. The decoders determine which word line and which sense amplifier are to be accessed. Buffer and control areas allow the device to be used by the outside world.

Figure 2. The layout of the various components of a TI 16K dRAM is indicated here.

The dRAMs were filled with a pattern of all 1's (hexadecimal FF loaded by the microcomputer into the memory space containing the dRAM.) or all 0's during both total dose exposure and for the upset measurements. Upsets were measured by filling the device, checking for correct fill, exposing to either the americium-241 alphas or the 3.3-MeV helium ions, checking for correct fill and noting the number of upsets and their addresses, refilling, and then checking for hard errors.

The mechanism of total dose damage to MOS devices is well established and is due to threshold shifts due to charge trapped in the oxide, and the formation of interface states¹³⁻¹⁵. This then changes the operating characteristics of the individual MOS devices that make up the integrated circuit device, until they are no longer able to perform their intended function. MOS capacitors on p-type substrates have been shown to exhibit negative threshold voltage shifts that move the characteristic capacitance versus voltage curve in the negative direction.¹⁶

RESULTS

Figure 3 is a graph of results obtained with a cobalt-60 exposure. The device was powered during irradiation and upset measurements have been made both for 00 fills and FF fills. It can be seen that the 00 upset rate was about an order of magnitude higher than the FF upset rate for all exposures. This asymmetry was seen in all cases and is not completely understood at the present time. Note that the upset rate decreased with increasing total dose exposure until an increase was seen in the FF upset rate near the end of the device's functional lifetime. Also note that the device was not functional after about 1.8 krad(Si). Figure 4 is the result of cobalt-60 irradiation of a device with power off. The same general features are seen as for Figure 3 except that now the device failed at about 3.0 krad(Si).

Figures 5 and 6 are results of powered and unpowered exposures and upset measurements similar to Figures 3 and 4, but performed with 3.3-MeV helium ions for both the total dose deposition and the upset measurements. The general features, namely greater 00 upset rate, decreasing upset rate with dose, and larger total dose failure level when unpowered, are the same as with cobalt-60 exposure. Although the FF upset rate is smaller than the 00 rate, it generally

Figure 3. Upset rate as a function of total dose delivered to the device by a cobalt-60 source. The bars represent statistical errors only.

Figure 4. Same as Figure 3 except that the device was unpowered during exposure to the cobalt-60 radiation.

shows a larger percentage reduction with accumulated dose. The percentage reduction for both the OO and FF upset rates was generally larger for ^4He irradiation than for cobalt-60.

Figure 7 shows the results of measurements on a Motorola dRAM to show that, although the details of this effect are somewhat different for different manufacturer's devices, the decrease in upset rate with total dose exposure is still observed. It is interesting to note that the OO and FF upset rates are approximately equal in this case. For powered dRAMs, the Motorola device failed at about 115 krad(Si) compared with 75 krad(Si) for the Texas Instruments device. Unpowered, the Texas Instruments device operated up to about 130 krad(Si). Note that these total dose failure levels are much larger than those for cobalt-60 irradiations.

In order to further investigate the mechanisms behind this decrease in upset sensitivity vs. total dose exposure, various areas of the dRAMs have been masked from exposure to the helium ion beam, both during total dose exposure and single event upset measurements. Figure 8 shows the results for a dRAM

Figure 5. Upset rate as a function of total dose delivered to the device by 3.3-MeV ^4He ions.

Figure 6. Same as Figure 5 except that the device was unpowered except during the brief exposure used to measure the upset rate.

where the inverted half of the memory and the sense amplifiers have been masked. Note first of all that no OO upsets were observed, consistent with the simple model of cell upsets that only 1-to-0 cell changes are possible, since a full well cannot absorb more charge. Note also that upsets are observed for the FF fill at a rate close to that observed previously for the comparable experiment without masking (Figure 4).

Figure 9 shows the results for a device which was first masked during exposure and then unmasked for the rest of the exposure. The masking of the normal half of the device and sense amplifiers (see figure 2) still results in a decrease in the upset rate with total dose exposure and produces upsets only for the OO fill (1-to-0 cell changes only). After an irradiation of about 17 krad(Si) the experiment was interrupted for three days and it can be seen that some annealing took place by the increase in the

Figure 7. Same as Figure 5 except that a Motorola dRAM was used here instead of a TI dRAM.

Figure 8. Upset rate measured with the inverted cell area and the sense amplifiers shielded from the incident ^4He ions.

upset rate. Continued exposure, however, resulted in a continued decrease. After 35 krad(Si) exposure, the mask was removed. Note that the upset rate for the OO fill increased indicating that some upsets are due to hits on the sense amplifiers and that the upset rate continued to decrease with continued exposure. Also note that the FF upset rate became measureable after mask removal and that it increased somewhat with total dose exposure, but because of the poor statistics this is not seen as a significant inverse trend to the general feature of decreasing upset rate with total dose exposure.

A further investigation of the upset sensitive areas is shown in Figure 10 where all of the auxiliary circuitry (the buffer, control, and decode circuitry at the ends of the dRAM, see Figure 2) was masked. Note that the basic features are still the same. The FF error rate here, although trending downward, exhibited an oscillatory pattern and seemed to depend on whether the preceding total dose exposure had been performed with an FF or a OO fill.

Figure 9. This plot demonstrates the annealing observed when irradiation of the dRAM was interrupted for three days, that is, upon resumption of the experiment the OO upset rate had increased toward its initial value.

Figure 10. Upset rate is measured with both the left and right ends (cf. Fig. 2.) of the dRAM shielded from the incident beam.

All of these data indicate that: 1) upsets are primarily due to ion strikes on cells or bit lines and not sense amplifiers themselves and 2) the decrease in upset rate because of total dose exposure is due to effects on memory cell capacitors, selection transistors, or bit lines.

DISCUSSION

Irradiation of an MOS device can result in long term changes in operating parameters due to both a buildup of charge in the oxide insulator and an increase in the number of interface states at the oxide-semiconductor interface. Both of these effects depend on the voltage applied to the device during irradiation, being largest for positive bias on the gate with respect to the semiconductor. Both of these effects result in a shift in the threshold voltage for inversion or a shift along the voltage axis in the capacitance versus voltage (C-V) characteristics of an MOS capacitor. In devices such as NMOS dRAMs, the shift due to the charge buildup is in the negative voltage direction, but the shift due

to interface states is in the opposite direction. Which one of these dominates depends on the quality of the SiO₂.

We believe that the observed decrease in upset sensitivity with total dose may be due to radiation-induced charge build-up in the gate oxide of the storage capacitor. Since the storage capacitor of a dRAM is in deep depletion, the depletion depth can be greater than its equilibrium value. The radiation-induced negative shift of the C-V curve results in an increased surface potential, a greater depletion depth, and hence more charge storage capacity. In other words the layer of trapped positive charge at the silicon-silicon dioxide interface results in a greater potential drop across the silicon and less across the oxide, when the total potential between the gate and the silicon substrate is kept constant. The device will operate correctly as long as sufficient current is provided to empty and fill the well within the required times, but the increased charge storage capacity will make the dRAM less sensitive to upset.

This speculation depends critically on the assumption of a net negative threshold voltage shift, which in turn depends on the importance of interface states which at this point is unknown for these specific devices. It is felt, however, that with the commercial processes used for these devices oxide charge will be the most important factor.

Eventually the threshold shifts will also affect the switching transistors and other aspects of device operation such that other failure modes take over which may be responsible for the increase in upset rate seen for some devices near the end of their lifetime. Since the results for cobalt-60 and helium ions was so similar, displacement effects are probably not an important factor.

As a byproduct of the SEU rate measurements, information was obtained on the total dose at which device failure occurs. For cobalt-60 gamma rays the power on and off doses to produce failure in TI dRAMs were about 1.8 and 2.7 krad(Si) respectively. The corresponding numbers for 3.3-MeV ⁴He ions were about 70 and 140 krad(Si). For Motorola dRAMs power-on failure under 3.3-MeV ⁴He ion bombardment occurred at 140 krad(Si). Two TI devices were also exposed (powered) to a 3.0-MeV proton beam. As expected, no SEUs were caused by the proton beam, but total dose failure was determined to occur at about 10 krad(Si). The fact that different doses are required for different forms of radiation to produce permanent failure of the device is believed to be due to different electron-hole recombination rates in the gate oxide layers. The ratio between the cobalt-60 gamma-ray and proton doses is in agreement with the measurements of Brucker et al¹⁷ which compare the effectiveness of various forms of radiation in producing threshold voltage shifts in MOS inverters.

Conclusions

These new results show that the SEU rate of MOS dRAMs decrease with total dose exposure, both for ⁴He ions and cobalt-60 gamma rays, a result unexpected on the basis of previous observations, which may be applicable to other electronic microcircuits. It also has been shown that backup devices carried on board a spacecraft and stored in an unbiased condition may experience a different variation of SEU rate than operating devices. The results have also confirmed that different forms of radiation have different effects on electronic microcircuits. Expressing the total dose hardness of

a circuit in terms of rad(Si) of cobalt-60 gamma rays will overestimate the radiation sensitivity of these circuits in those space environments where protons and cosmic ray heavy ions are the major factors.

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