USE OF AN ION MICROBEAM TO STUDY SINGLE EVENT UPSETS IN MICROCIRCUITS

by

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Abstract

A beam of energetic ions has been used to study the upset sensitivity of various device elements on 16K dynamic RAMs. Small beam defining apertures, ranging in size from 2.5 micrometers in diameter to a 250 by 1100 micrometer rectangular aperture, were used to produce microbeams of protons, helium ions, and nitrogen ions, although most of the work reported here was conducted using helium ions. Upset rates were measured as a function of 4He ion energy from 1.6 to 3.5 MeV on different areas on the same device and on devices from different manufacturers. Different threshold energies and sensitivities were found for sense amplifiers, normal cell areas, and inverted cell areas. In the course of the upset measurements an important new effect was observed, namely that the sensitivity of microcircuits to single event upsets can be increased as a result of the accumulation of total dose in the device.

Introduction

Soft errors or single event upsets represent one important limitation to the reliability of VLSI microcircuitry of the future. The trend is to put more and more elements onto a single device chip through device scaling. This practice has resulted in microcircuits which contain ever smaller individual device elements with correspondingly smaller capacitances. In keeping with scaling laws, the operating voltage is also reduced and the amount of charge necessary to switch an individual element is reduced. When this switching charge is small enough that an individual energetic charged particle can deposit an equivalent amount at a node, soft errors can occur. In some cases the effects of the energetic particles can be reduced by shielding (in some cases the shielding is a coating on the chip itself), but once the practical limit of this method is reached the best way to reduce the soft upset rate further is through the use of special design techniques. Some techniques minimize charge collection at nodes by using buried layers, while others reduce sensitivity by increasing the cell capacitance. One of the most important is related to the critical charge. Energetic charged particles are present in the form of extremely penetrating cosmic rays and may cause a lower limit to the reliability of the entire integrated circuit in terms of failures per device hour. In a low altitude satellite environment (electrons or protons in the Van Allen belts) or nuclear weapon environment where the flux of particles is higher than in the normal terrestrial environment and the particles are more penetrating, the soft error rate may be prohibitively high. Thus an understanding of the processes which produce single event upsets can aid in the design of more reliable devices in the future.

Energetic alpha particles have been shown to be capable of inducing soft upsets directly in microcircuit devices. Such upsets are caused by


The experiments reported on here were undertaken in order to illustrate the value of using an ion microbeam to understand the basic mechanisms of charged particle induced single event upsets better. A beam of energetic particles, with dimensions comparable to those of various device elements or structures, is directed onto a device chip and the upset rate is measured as a function of the location on the chip and the beam energy. In this way the upset sensitivity of various sections of the device can be determined.

Because of the amount of previous work reported on alpha induced single event upsets in N-channel MOS 16K dynamic RAMs, these microcircuits and 4He ions (alpha particles) were chosen for a first experiment. Most of the present results are for 1.6-3.5 MeV helium ion bombardment but some results will be presented for MeV protons and nitrogen ions. Devices from various manufacturers were studied by operating them as a part of the memory of a microcomputer system.

All of the 16K dynamic RAMs tested were of the double level polysilicon design with aluminum metallizations and are divided into two memory halves separated on the chip by sense amplifiers or decoders. Individual MOS cells are connected to decoders or sense amplifiers via polysilicon, metal, or diffused lines which are shared with other cells. Some neighboring cells share common polysilicon gates and word lines. One manufacturer's device was designed with folded bit lines. The cell areas are divided such that one half of the memory, referred to as the normal half, represents a "1" by a cell depleted of electrons and a "0" by a cell with a normal complement of electrons. The other half, referred to as the inverted half, uses the inverse representation.

Experimental

Energetic ion beams for these experiments were provided by the NRL 5-MV Van de Graaff. In the measurements reported here high-voltage breakdown problems prevented the attainment of beam energies higher than about 3.7 MeV. In addition to the standard radio-frequency ion source, a Hill-Wilson source is also available, so that ion beams of almost any element in the periodic table may be produced.

The setup used for most of the present measurements is shown in Figure 1. The magnetically
analyzed beam from the Van de Graaff passes through a scattering foil, typically 250 to 6000 angstroms of Ni. A surface barrier counter detects beam particles scattered at 135° to the incident direction and serves as a monitor of beam intensity and total fluence. Beam particles scattered horizontally through a small angle, θ, pass through a square collimating aperture 7 mm on a side and then reach the aperture which defines the area of the device exposed to the beam. This aperture can be translated in the two directions normal to the incident particles. The surface of the device is usually less than 1 mm beyond the aperture. The device is mounted on a carrier suspended from an x-y-z translation stage which can be rotated about a vertical axis. In these experiments, however, normal incidence was always used. The carrier is a surface barrier detector which can be positioned to replace the device behind the defining aperture, thus allowing one to determine the ratio of the number of ions passing through the aperture and striking the device to the number of ions counted in the monitor detector. The device is positioned with respect to the aperture by observing the position of the aperture relative to the microscope reticle. The aperture is then moved out of the way and the device is translated so that the area of interest is located at the same position on the reticle. The limited depth of field of the microscope requires that the device be at the same position along the beam as the aperture. The z translation stage is then used to move the device back along the beam, the aperture is restored to its former position and the device is translated forward until it almost touches the aperture. The portion of the apparatus enclosed by the dashed line in Fig. 1 is mounted on a translation stage to allow changing the scattering angle. Because the scattering cross section varies rapidly with angle, changing the angle allows variations of the particle flux incident on the device. The device is mounted inside a vacuum system at about 10^-5 torr.

Aperture sizes ranging from a 2.5 micrometer diameter pinhole in 12.5 micrometer thick stainless steel to a 250 by 1100 micrometer rectangular aperture were used. The long dimension of the rectangular aperture and the long dimension of the RAM chip were both oriented in the vertical direction. Measurements of beam divergence after passing through the aperture were performed with a 25 micrometer diameter pinhole aperture by placing a movable 5 micrometer diameter pinhole over the surface barrier detector behind the aperture. With the 5 micrometer pinhole almost in contact with 25 micrometer pinhole and with a separation of 2.75 mm, the full width at half maximum of the transmitted particles was 22 micrometers in the vertical direction and 28 micrometers in the horizontal. This measurement indicated that the divergence of the beam after it passed through the aperture was small.

On the carrier for the devices shown in Fig. 1 is a 16 pin DIP socket with decoupling capacitors appropriate for 16K dynamic RAMs mounted on the three power supply pins. The delidded devices mounted in the DIP socket are connected to the test system with about 10 inches of cable through a vacuum feedthrough. Matching resistors (100 ohms) are placed at the transmitting end of each signal lead. The device being tested is one of eight 16K dynamic RAMs comprising a 1K portion of the memory of a Zilog 280-MCB microcomputer system operating at a clock frequency of 2.5 MHz. The portion of the memory containing the test device is filled with either all "0"s or all "1"s and a program in the microcomputer checks for any changes from the original data and determines the memory address of any changed bits. From bit maps supplied by the manufacturers, these addresses can be converted to locations on the chip itself. This also allows the state of an individual cell to be determined since filling a device with all of one character will result in one-half of the RAM being in the "1" state and the other half being in the "0" state. The devices tested were Texas Instruments TMS 4116-25JL, Motorola MCM 4116-82C0 and Fujitsu MB 8116C. During the operation of the test program, each cell is refreshed about every 200 microseconds.

**Results**

Initial measurements were performed with a 2.5 micrometer aperture, but we became concerned that in the process of obtaining adequate statistics on the upset rate in a particular area of the RAM, permanent damage, sufficient to influence the upset rate, could result. To obtain an estimate of the point at which this might occur, the 4He ion fluence required to produce a hard or permanent failure was measured. These data were obtained with a 25 micrometer diameter aperture and are presented in Table I. The dose was computed assuming the damage to be uniformly distributed along the path of the 4He; the values calculated in this way can be compared to total dose failure levels measured with other forms of radiation. With bremsstrahlung, hard

![Diagram](image)

**Figure 1.** Shown here is the experimental set-up used to produce small area beams to measure upset rates on selected areas of dynamic RAMs.
failure levels of about 4 Krad(Si) were measured for Motorola devices and the total dose failure level of about 2-4 Krad(Si) was measured with Co-60 irradiations of some similar 16K dynamic RAMs. The reason for this difference (the Motorola devices were measured as about a factor of 60 "harder" in the 4He microbeam) is not at present understood, but may be at least in part related to charge recombination effects. Electron-hole recombination in the oxide is more efficient for the denser ionization path of the 4He ion, and if the failure mechanism is due to holes trapped at the silicon-silicon dioxide interface, then the higher failure dose in terms of Rads(Si) for the helium ion case is reasonable.9,10,11

Hard errors were observed in all devices tested when the beam was directed at the cell area or the sense amplifier area. The number of ions needed to produce hard errors was not accurately determined in the case of the inverted cell area and sense amp area of the Texas Instruments RAMs so these data do not appear in Table I. Hard errors in the cell areas involved two or three adjacent cells (almost never a single cell). In the cell area of the Motorola devices at a 4He energy of 2.30 MeV, no soft failures were observed prior to the hard failure. Hard failures in the sense amp area usually involved about 100 cells.

Using a 2.5 micrometer diameter beam, it was shown that by directing the beam at only a single cell (or possibly two because of a shared poly level) of a Texas Instruments RAM, the upsets were transmitted via the bit lines to cells sharing a common sense amplifier.

Figure 2 shows the energy dependence of the upset rate measured on both cell areas and the sense amp area of two Texas Instruments RAMs. The 250 by 1100 micrometer rectangular aperture was used for these measurements. With the aperture positioned on the inverted cell area no upsets were observed with the memory filled with "1"s, indicating an upset rate more than a factor of 20 lower than for a "0" fill. There appears to be a threshold for the occurrence of upsets at about 2.3 MeV. The energy threshold for producing upsets in the sense amp area is substantially lower than in the cell area. The normal cell area seems to have an upset threshold around 3.0 MeV, substantially higher than for the inverted area and the upset rate is about an order of magnitude lower than in the inverted cell area. The energy threshold for producing upsets in the sense amp area is substantially lower than in the cell areas.

The energy dependence of the upset rate as measured in the sense amplifier area of two Motorola RAMs is shown in Fig. 3. Consider first the data plotted with diamond (♦) symbols. As in the case of the Texas Instruments RAMs, the upsets were spread out over 37 columns, a result consistent with the size of the rectangular aperture. The RAM was translated vertically to a new area after these measurements and a similar measurement was performed on the cell area. Examination of the upset addresses showed that all the upsets had occurred in one particular column, although they were distributed over virtually all rows. This indicates that one sense amp was the most upset prone and upsets were transmitted to all rows via the bit line. A second vertical translation to a new area produced no upsets for $1.5 \times 10^5$ 3.54-MeV 4He ions. Measurements on a second Motorola RAM (data not shown here) yielded an upset rate which was about 1/3 of that measured on the first RAM. No upsets were observed in the cell area of the second RAM.

A third Motorola RAM which had been exposed to a fluence of about $2 \times 10^7$ 4He ions over a 1 mm square area showed no hard upsets but a much higher soft upset rate in the sense amp area. The energy dependence of this upset rate is shown in Fig. 3 (square symbols). It is believed that this higher upset rate is due to the total ionizing dose produced.
Considerable variation has been observed in the upset sensitivity of 16K dynamic RAMs produced by different manufacturers and even in RAMs produced by the same manufacturer with the same date code.

For $^4$He energies below about 2.8 MeV, the sense amp region of two Texas Instruments RAMs had a higher upset sensitivity per unit area than the cell area, and the inverted cell area was considerably more sensitive than the normal cell area. The sense amp area was also observed to be more sensitive than the cell area in several Motorola RAMs.

Measurements of the dose which is required to cause a hard failure indicate that this effect will make it difficult to measure soft upset rates with good statistics and high spatial resolution. Even with 25 micrometer resolution, a dimension which encompasses an entire memory cell, and with a device relatively sensitive to upsets, the dose (i.e., fluence of particles) required to produce a hard failure only produces of the order of ten soft upsets. A possible method of alleviating this problem is to take data on a number of equivalent areas of the device, while exposing each area to only a small fraction of the dose required to produce a hard failure. Another method which should prove useful for some areas of the devices such as bit lines, is the use of a pulsed incident beam which can be synchronized with internal clock pulses to increase the beam's effectiveness in producing soft upsets, hence reducing the fluence required to produce a given number of upsets.

The highest upset rate measured for the Texas Instruments devices was about one upset per 1000 $^4$He ions at about 3.5 MeV. In the case of the Motorola devices, the highest upset rate was one upset per 2500 $^4$He ions at about 3.5 MeV, but after exposure to $2 \times 10^7$ $^4$He ions this rate increased to about one upset per 150 $^4$He ions. Yaney et al. measured upset rates in 16K dynamic RAMs by exposing the entire device to alphas of varying energies from a radioactive source. Assuming a device area of 1 cm$^2$ and using their flux of $5.1 \times 10^3$ particles/cm$^2$-min, they measured rates as low as one upset per 5 x $10^4$ alphas and as high as one upset per 125 alphas depending on the device and operating conditions (duty cycle and operating voltage). Thus our results are in reasonable agreement with these earlier results which indicate that only a small fraction of the incident alphas produce upsets.

In the course of these experiments, a new and important effect was observed, namely that the sensitivity of the sense amplifier area of a device to single event upsets was increased by a factor of approximately 20 after the device was exposed to $2 \times 10^7$ $^4$He ions over a 1 square millimeter area. This ion fluence is about one third of the fluence necessary to produce hard errors. This result suggests that measurements of the upset rate as a function of total dose exposure will need to be performed for applications, such as occur in space systems, in which devices are expected to accumulate significant amounts of total ionizing dose.

Conclusions

It has been shown that a microbeam of energetic ions with dimensions comparable to those of individual device elements can provide useful information on the upset sensitivity of microcircuits.

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References


11. Leon S. August, Naval Research Laboratory, private communication.