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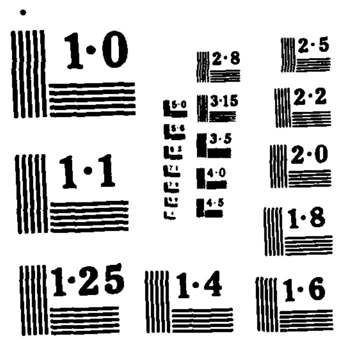

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MICROCOPY RESOLUTION TEST CHART

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(12)

Clarkson University
POTSDAM • NEWYORK 13676

November 12, 1985

Dr. E. Peterson
Naval Research Laboratory
4555 Overlook Ave, SW
Washington, DC 20375
ATTN: Code 6611

RE: Contract Number: N00014-84-C-2318

Dear Dr. Peterson:

Enclosed please find a copy of the final technical report for the above contract number.

If you have any questions, please feel free to contact me at the number below.

Sincerely,

Catharine L. Owen

Catharine L. Owen
Director
Grants and Contract Services
(315) 268-6469

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Enclosure

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cc: Dr. McNulty
Vickie Chesley
Code #2627
DTIC

NOV 7 1985

Final Report

ENERGY DEPOSITION IN GALLIUM ARSENIDE

Prepared by
PETER J. MCNULTY
PROFESSOR OF PHYSICS
CLARKSON UNIVERSITY
POTSDAM, NEW YORK 13676

Agency: Naval Research Laboratory

Contract Number: N00014-84-C-2318

Table of Contents

1. BACKGROUND

This report pertains to

We have been studying the single-event-upset phenomena in microelectronic circuits with emphasis on those resulting from nuclear reactions induced by energetic protons ~~(1-3)~~. Our goal is to understand the detailed physical mechanisms leading to SEUs sufficiently to put calculating SEUs on a sound quantitative basis. We previously had considerable success in predicting the charge generation in well defined slabs of silicon ~~(4-6)~~. The purpose of this contract was to try extending the model and the associated simulation codes to GaAs and to begin the experimental measurements necessary to test them.

2. ACCOMPLISHMENTS UNDER THE CONTRACT

The Clarkson Nuclear Reaction models were modified to handle proton-induced nuclear reactions in gallium arsenide ~~(7)~~. For detail, see Appendix A.

The codes were immediately useful in analyzing the significance that the "edge-effect" phenomena, discovered in microbeam studies of GaAs gates, would play in increasing the SEU rates for GaAs memories ~~(8). See Appendix B.~~ Techniques were ~~We~~ developed ~~techniques~~ using these codes for calculating SEU rates for select circuits flown in space (9). Two of these circuits, the 2901B and the 93L422 are responsible for SEU problems aboard US satellites. For details see Appendix C.

Charge-Collection Measurements have been carried out using the GaAs Fat-FET test structures from the Rockwell memories. The first round of measurements are completed and a paper is being prepared for publication. There is excellent agreement between theory and experiment at high incident proton energies but poor agreement at lower proton energies. A comparison of theory and experiment is given in Fig. 1 for protons incident at 148 MeV. The fit is typical for energies above 60 MeV.

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9. P.J. McNulty, W.G. Abdel-Kader, and J.M. Bisgrove, "Methods for Calculating SEUs in Bipolar and NMOS Circuits" IEEE Trans. Nuc. Sci. to be published.

4. PAPERS PUBLISHED UNDER THIS CONTRACT

1. "Microdosimetric Analysis of Proton-Induced Reactions in Silicon and Gallium arsenide" G.E. Farrell, P.J. McNulty, and W.G. Abdel-Kader, IEEE Trans. Nuc. Sci. NS-31, 1128-1131 (1984)

2. "Charge Collection in Gallium Arsenide Test Structures" P.J. McNulty, W.G. Abdel-Kader, A.B. Campbell, A.R. Knudson, P. Shapiro, F. Eisen, and S. Roosild, IEEE Trans. Nuc. Sci. NS-31, 1128-1131 (1984).

3. "Methods for Calculating SEUs in Bipolar and NMOS Circuits", P.J. McNulty, W.G. Abdel-Kader, and J.M. Bisgrove, IEEE Trans. Nuc. Sci. to be published.

Appendix A

IEEE Transactions on Nuclear Science, Vol. NS-31, No. 6, December 1984

MICRODOSIMETRIC ANALYSIS OF PROTON INDUCED REACTIONS IN SILICON AND GALLIUM ARSENIDE

G. E. Farrell
Physics Research Division
Emmanuel College
400 The Fenway
Boston, Massachusetts 02115

P. J. McNulty and Wagih Abdel-Kader
Physics Department
Clarkson University
Potsdam, New York 13676

ABSTRACT

Microdosimetric comparisions of volumes of silicon and gallium arsenide exposed to protons of 25 to 300 MeV have been performed using a computer simulation. Significant differences between silicon and gallium arsenide are seen in the energy-deposition spectra. The effect of the surrounding material, the energy and mass spectra of the recoiling nuclei, and the effect of scaling are also presented and discussed.

INTRODUCTION

Radiation-induced errors in microelectronic circuits have in recent years been recognized as a serious problem. Charged particles lose energy by ionizing the medium through which they pass, leaving behind a wake of electron-hole pairs. The sudden introduction of this charge into a microelectronic device can result in errors known as single-event upsets (SEU's). The energetic protons in the radiation belts and in the cosmic rays can induce SEU's, either directly or through secondary particles from nuclear reactions. The most important secondary particle emerging from a proton-induced nuclear reaction, at least as far as SEUs are concerned, is the recoiling fragment of the target nucleus. The prediction and control of these upsets is crucial to the functioning of satellite systems, and our ability to quantitatively model SEUs sufficient to accurately predict rates will depend ultimately on the ability to model the deposition of energy and the consequent generation of charges in microvolumes of given dimensions.

An SEU will occur if an ionizing particle deposits more than a critical amount of charge within one of the sensitive microscopic volume elements on a device. We previously presented theoretical energy-deposition spectra generated in silicon by nuclear interactions initiated within the sensitive volume (1-3). These calculations were compared to experimental data obtained using Ortec silicon surface-barrier detectors, all with a cross sectional area of 25 mm^2 and thicknesses ranging from 2.5 to 97 micrometers exposed to protons ranging in energy from 25 MeV to 158 MeV. The agreement was quite good.

*Work supported by Air Force Contracts No. F19628-82-K-0039 from the Air Force Geophysics Laboratory and F19628-82-K-0004 from the Rome Air Development Center.

In this paper we extend the calculations to gallium arsenide and we include, for both Si and GaAs, the contributions from interactions that are initiated outside the sensitive volume. We find for both materials that the contributions from interactions initiated in the surround are important for all but the highest energy depositions.

COMPUTER MODEL

A Monte-Carlo type computer simulation was used to model the nuclear reaction initiating the SEU. The physical assumptions upon which these codes are based are similar to those of the codes developed by Metropolis et al. (4), Dostrovsky et al. (5), Bertini (6-9), and Guthrie (10,11). In our model, all the secondary charged particles emerging from the nuclear event are followed to determine how much, if any, energy is deposited in a sensitive volume of specified dimensions. Then the total energy deposited is summed over all the secondaries emerging from each reaction to obtain the total energy deposited in the sensitive microvolume by ionization losses by the charged secondaries emerging from that event.

The small defined sensitive volume of silicon or gallium arsenide corresponds to one sensitive region on a microelectronics chip. The sensitive volume is embedded as shown in Fig. 1 in a larger volume which represents the rest of the chip. In the simulations discussed here, a unidirectional beam of protons of a given incident energy is sent into the large volume. Some of these protons will pass through the sensitive volume and deposit energy there, a small fraction will undergo nuclear reactions in the sensitive volume, and other protons will induce nuclear reactions elsewhere in the larger volume. Both secondary particles and a recoiling nuclear fragment result from these reactons and some of these traverse the smaller sensitive volume.

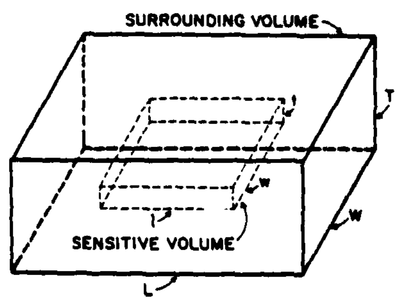

Fig. 1. Sensitive volume embedded in larger surround. Model calculates the energy deposited within the sensitive volume by charged particles emerging from nuclear reactions initiated anywhere within the larger volume.

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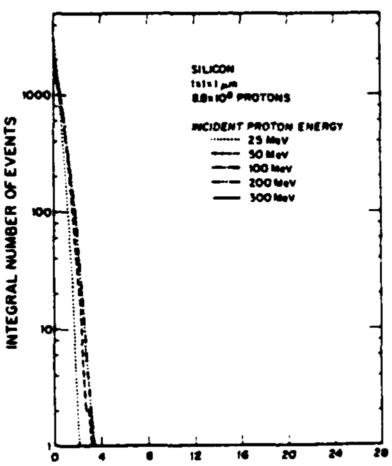
The paths of all of the charged secondaries are followed in the simulations to determine whether they cross the sensitive volume. A spectrum of the energy deposited in the sensitive volume per nuclear interaction is thereby obtained.

We previously reported that, according to our simulation model, the energy-deposition spectra for thin slabs of silicon are dominated by contributions from the nuclear recoil. This conclusion appears to be true for large energy depositions in GaAs also. It should be noted that the model assumes the sensitive volume to have the shape of a rectangular prism, while the detectors used in the experimental measurements are cylindrical slabs. The difference does not appear to be significant.

RESULTS

Figures 2a and 2b compare the integral energy-deposition spectra in one micrometer cubes of silicon and gallium arsenide. Figures 2c and 2d make a similar comparison for 10 micrometer cubes. For both simulations the exposures were to unidirectional beams of protons incident normal to the cube face with energies of 25, 50, 100, 200 and 300 MeV. These calculations include only inelastic nuclear reactions initiated inside the sensitive volume and do not include contributions from reactions in the surround. Comparison shows that for the lower proton energies considerably more energy is deposited in the silicon volumes than the corresponding gallium-arsenide ones. For the 10 micrometer cube exposed to 25 MeV protons the number of events in which more than 2 MeV is deposited is nearly 50 times larger in the silicon than in the gallium arsenide. The explanation for this is in the nuclear kinematics. Gallium and arsenic are more massive than silicon, and it is kinematically more difficult to give them as much recoil energy as to a silicon nucleus. The model also predicts that silicon reactions at these energies emit a sizable proportion of charged secondary particles while the secondaries from gallium arsenide are mostly neutrons.



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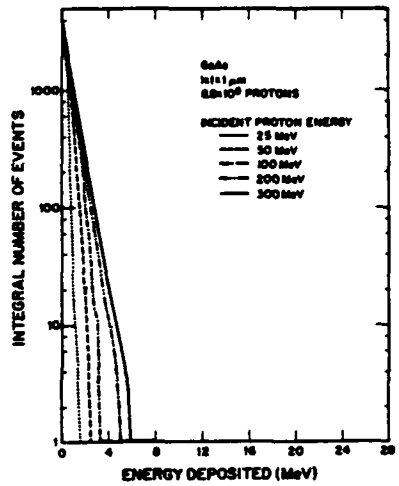

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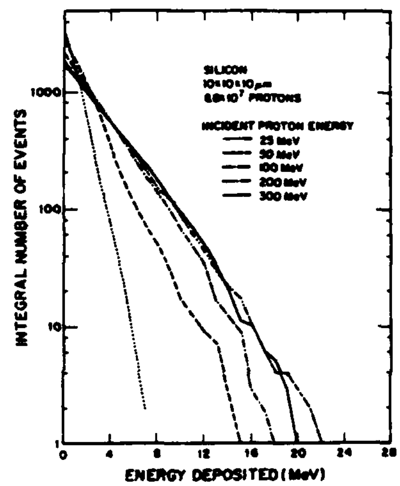

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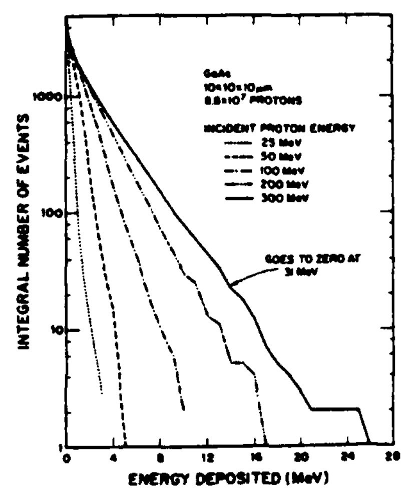
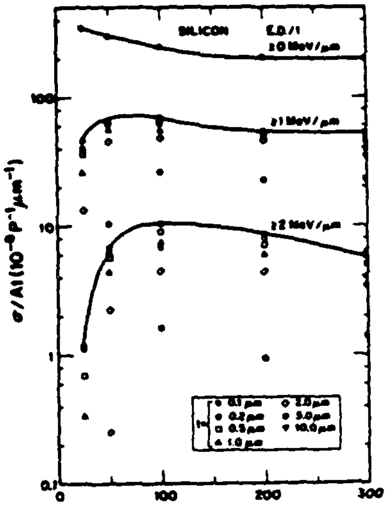


2.d

Fig. 2. Integral energy-deposition spectra for protons of different incident energies incident on a) a one micrometer cube of silicon, b) a one micrometer cube of GaAs, c) a 10 micrometer cube of silicon, and d) a 10 micrometer cube of GaAs. No surround.

At higher incident proton energies, especially for smaller sensitive volumes, the long-range silicon nuclei leave the sensitive volume before depositing all of their energy. The gallium and arsenic recoils, being shorter, tend to remain inside and this leads to greater energy depositions in the smaller GaAs volumes than in silicon volumes of the same dimensions. This is seen in comparing the corresponding curves in Figs 2a and 2b. If the sensitive volume has larger dimensions a greater fraction of the silicon recoil remains inside and the energy depositions are larger for Si than for GaAs as can be seen for 10 micrometers in Figs. 2c and 2d. Only for the highest energy depositions in the 10 micrometer cubes do the GaAs curves equal the corresponding Si ones.



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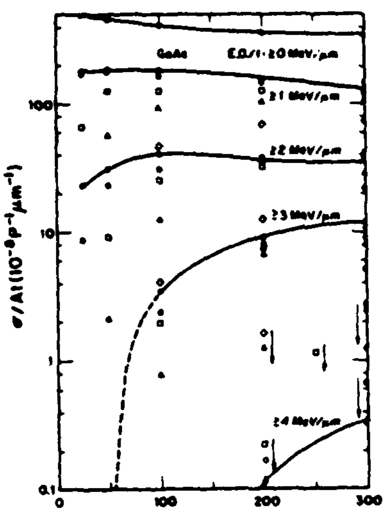


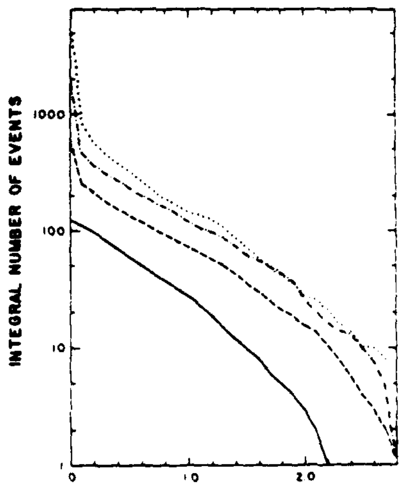
3.b

Fig. 3. Ratio of the cross section for depositing at least some value, E.D., in a cube of a) silicon and b) GaAs for dimensions t on a side versus the energy of the incident proton for different values of E.D./t and t. Volume expressed as At where $A = t^2$.

One goal of our research effort is to determine how the energy deposition in a sensitive volume scales with feature size. A simple approach to scaling is illustrated in Fig. 3 by plotting the ratio of the cross section for some threshold energy deposition, E.D., in a cube of dimensions, t, to the volume of the cube as a function of incident proton kinetic energy for various values of E.D./t. Since the probability for inelastic interactions per unit volume is uniform over the range of sizes considered, the data for E.D./t > 0 for all values of t lie on the same curve. One can thus obtain the cross section for a nuclear reaction in a microvolume of arbitrary area A and thickness t by multiplying the abscissa value by A t. Such simple scaling also appears to hold for small energy depositions in small microvolumes but not for larger energy depositions in thicker microvolumes. The data for E.D./t > 1 MeV per cubic micron fall on the same curve for smaller cubes but not for the largest. As E.D./t increases the divergence for the larger cube sizes increases quickly.

Effects of Surround

A closer approach to real conditions in a chip is made by embedding the small sensitive volume in a larger volume as in Fig. 1. For sufficiently small sensitive volumes, most of the energy deposited will come from interactions initiated outside of the sensitive volume. In Fig. 4a are shown the calculated integral energy-deposition spectra in silicon for a cubic sensitive volume of one micron with no surround, and for the same volume embedded in a 2 micron cube, a 4 micron cube, and an 8 micron cube- all of silicon. The corresponding curves for gallium arsenide are shown in Fig. 4b. The low energy depositions are due to secondary particles, while nuclear recoils dominate at higher energy depositions. The gallium arsenide data in Fig. 4b show little increase as the large cube is increased from 2 microns to 8 microns, except at the smallest energy depositions where the long range secondaries dominate.



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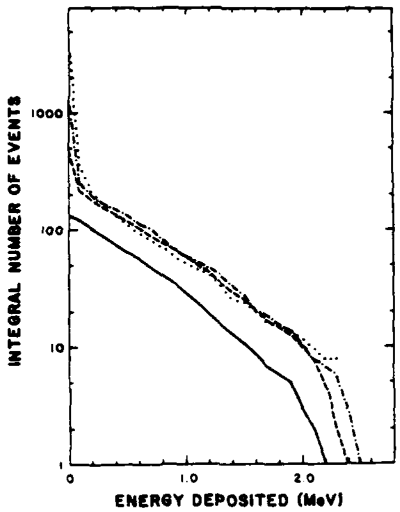
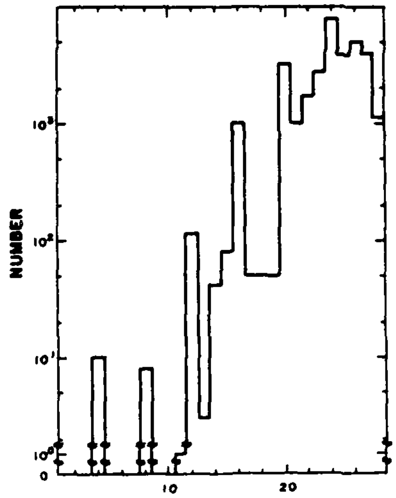


4.b

Fig. 4. Integral spectra for energy deposited in a one micrometer cube of a) silicon and b) GaAs as a result of protons incident at 100 MeV. The solid curve includes only the contributions from nuclear reactions initiated within the cube itself; the dashed curve includes energy depositions in the cube from secondaries emerging from events initated within one micrometer of the cube; the dot-dashed curve includes contributions from events intiated within 2 micrometers; and the dotted curve includes contributions from events initiated within 4 micrometers of the cube. The surround is assumed to be the same material as the cube.

In silicon, events generated far from the sensitive volume contribute significantly, as seen in Fig. 4a. This is presumably due to the longer range of the recoiling nuclear fragment following a nuclear reaction in silicon. If one is concerned with lower energy depositions (for example, circuits sensitive to alpha particles) then the effect of energetic charged secondaries is more important. In that case the contribution from reactions initiated within a few hundred microns of the sensitive volume must be included.

Most of the large-energy-deposition events are due to the traversal of the sensitive volume by the recoiling nuclear fragment. The fragment deposits all or most of its energy within a short distance and is, *thereby, a source of large energy depositions.* Figures 5a and 5b are calculated histograms of the atomic mass spectra of the nuclear fragments resulting from proton-induced nuclear reactions in silicon and gallium arsenide for an incident energy of 100 MeV. The energy spectra of the recoiling heavy fragments emerging from these reactions are plotted for silicon and gallium arsenide in Figs. 6a and 6b, respectively. The recoils in GaAs have lower energies and correspondingly shorter ranges than those in silicon; as a result, the stopping power or linear energy transfer (LET) of a recoil in GaAs is typically higher than for a recoil in silicon. If the smallest dimension of the sensitive volume is smaller than the range of the typical recoil, the LET determines the energy deposited in the sensitive volume and larger energies will be deposited for the same dimensions in GaAs; if, on the other hand, the smallest dimension is larger than the range of the energetic recoils, the total energy carried by the recoil determines the energy deposited and larger energies will be deposited if the sensitive volume lies in silicon.



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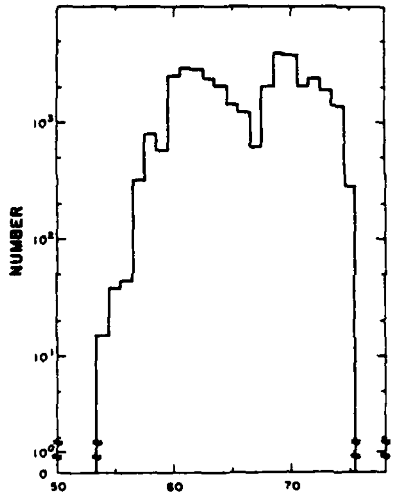
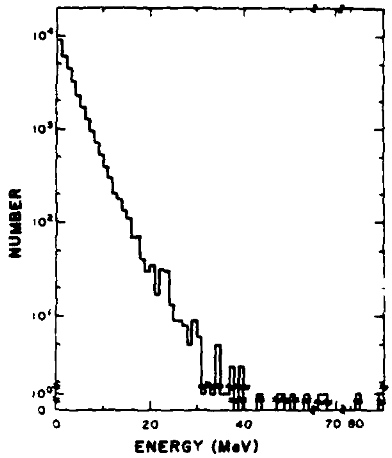


5.b

Fig. 5. Distribution in atomic mass number of the recoiling nuclear fragments following nuclear interactions of 100 MeV incident protons in a) silicon and b) GaAs.

SUMMARY

Theoretical energy-deposition spectra from proton-induced nuclear reactions in microscopic volumes of silicon and gallium arseni e have been calculated. The computer model has previously been shown to give good agreement with experimental values from silicon. Greater energy depositions are seen in silicon for low incident proton energies and large sensitive volumes, while gallium-arsenide reactions deposit more energy at the higher incident proton energies in small sensitive volumes. The effect of the surround is particularly important with silicon, as the residual nuclei from silicon reactions can have long ranges but, even in GaAs, the contribution from nuclear reactions initiated *outside* the sensitive volume will exceed the contribution from those initiated within for circuits having *LSI geometries.*



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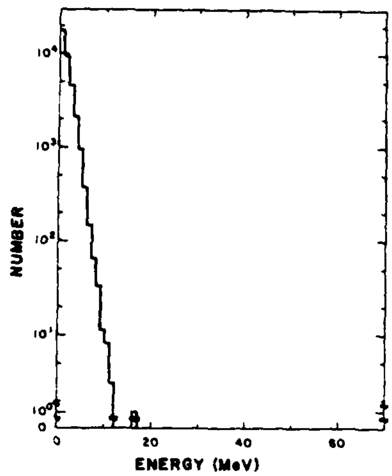

6.b

Fig. 6. *Distribution of the kinetic energy of the recoiling nuclear fragment following interactions between 100 MeV protons and a) silicon nuclei or b) GaAs nuclei.*

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Appendix B

IEEE Transactions on Nuclear Science, Vol. NS-31, No. 6, December 1984

CHARGE COLLECTION IN GA/AS TEST STRUCTURES*

P. J. McNulty and W. Abdel-Kader
Clarkson University
Potsdam, New York 13676

A. B. Campbell, A.R. Knudson, and P. Shapiro
Naval Research Laboratory
Washington, D.C. 20375

F. Eisen
Rockwell International
P.O. Box 1085
Thousand Oaks, CA 91360

S. Roosild
Defense Advanced Research Projects Agency/DSO
Arlington, VA 22209

ABSTRACT

Evidence is presented for enhanced charge collection near the edges of large-area test structures on Rockwell's GaAs 256 bit memory devices when held at high bias. Simulation calculations show that such enhanced charge collection at the edges of critical structures could lead to greatly increased SEU rates in space.

INTRODUCTION

Microelectronic circuits based on GaAs technology have intrinsic advantages in speed and relative insensitivity to radiation over comparable silicon-based circuits. However, single event upsets (SEUs) have recently been observed when GaAs circuits have been exposed to energetic protons, presumably as a result of proton-induced nuclear reactions in the speed-up capacitors or under the gates of the field-effect transistors (FETs). The standard model of proton-induced SEUs involves nuclear reactions between the protons and the nuclei of the atoms making up the circuit elements and the generation of numerous electron-hole pairs along the trajectories of all the secondary charged particles emerging from the event, especially the recoiling nuclear fragment (1). The condition for an event, according to this model, is the collection of more than a critical charge across depletion region formed under one of the SEU sensitive gates under bias. When the target material is GaAs, the recoiling nuclear fragments have higher charge, lower energy, and much higher LET compared to the equivalent circuit elements formed in silicon (2).

A computor-simulation model developed at Clarkson for energy deposition in silicon microstructures (3) has recently been extended to GaAs microstructures (2) inviting comparison between theory and experiment. This comparison requires detailed knowledge of the dimensions of the device's sensitive microvolumes, within which the charge generated contributes to the probability of an SEU. Most SEU models (1-6) postulate the existence of sensitive volumes associated with certain depletion regions on the device where the geometry of the sensitive volume is usually assumed to be similar to that of the depletion layer with the dimensions extended beyond the depletion layer somewhat to account for the diffusion of charges into the depletion region. Of course, simple extension of the assumed sensitive volume beyond the depletion region is not expected to be sufficient to account for any contributions to the charge collected across the depletion region through field-assisted drift, either along the trajectory of the secondary charged particles or at the edges of the sensitive microstructure. There is evidence for large regions of intense fields which extend considerable distances beyond the edges of the MESFET gates (7) and p-n junctions (8) in GaAs.

This work supported by Air Force Contract No. F19628-82-K-004 from Rome Air Development Center and by the DAPRA/DNA Single Event Upset Program.

The purpose of this report is to present evidence of enhanced charge collection at the edge of GaAs test structures and to describe some implications of such field-assisted drift on the sensitivity of devices to proton-induced upsets.

EXPERIMENTAL MEASUREMENTS

The test structure used in this study was a large field effect transistor (FET) with a gate having lateral dimensions of 138 micrometers wide by 328 micrometers long; this is the "Fat FET" test structure from the same wafers as Rockwell's 256 bit GaAs RAM device. It received their N- (selenium) implant, for which a typical doping profile is shown in Fig. 1. It is compared in the figure with the doping profile corresponding to their N+ (sulfur) implant. The dashed curve represents the profile when both the N- and N+ implants are carried out. The area surrounding the Fat FET is covered by a layer of sputtered silicon nitrite. No proton bombardment was used for isolation.

The charge collection efficiency of various test structures were measured as a function of position by exposing the device under test to 1.6 MeV helium ions collimated by means of a beam defining aperture of 2.5 micrometers diameter. These measurements were carried out using the microbeam facility established at the NRL's Van de Graaff accelerator.

The signal which resulted when the test structure was traversed by a helium ion was processed by a charge sensitive preamplifier connected to a shaping amplifier with the resulting signal recorded by a pulse height analyzer, just as if the test structure were a nuclear solid state detector. The collection efficiency was defined to be the ratio of the measured signal to that measured with the same electronics when identical beam particles are stopped in a silicon detector. No correction was made for the difference in W values (average energy deposited per electron-hole pair) between the two materials.

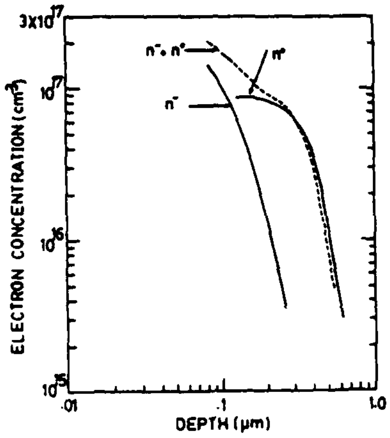

FIG. 1. Doping profiles for the N- (selenium) and N+ (sulfur) implants.

Figure 2 plots the collection efficiency measured for charge collected on the gate of a Fat FET test structure as a function of position along the gate width. The right edge of the gate lies at approximately +15 micrometers in the figure. Similar results were also seen for the N+ structure. Apparently the charge collection increases as the microbeam probes locations near and beyond the edge of the gate. For the measurements shown in Fig. 2, the source and drain were grounded and the gate biased at - 1.2 volts.

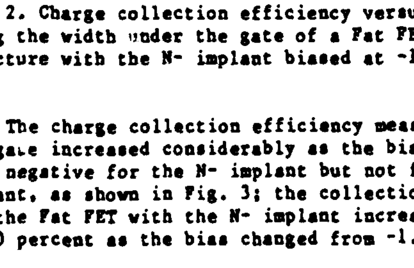

Fig. 2. Charge collection efficiency versus position along the width under the gate of a Fat FET test structure with the N- implant biased at -1.2 volts.

The charge collection efficiency measured under the gate increased considerably as the bias became more negative for the N- implant but not for the N+ implant, as shown in Fig. 3; the collection efficiency for the Fat FET with the N- implant increased from 15 to 20 percent as the bias changed from -1.2 to -1.75 volts. Measurements along the length of the N- gate show enhancements of about 50 percent when the microbeam probes reach the edge, as shown in Fig. 4 for a gate bias of -1.75 volts with the edge at approximately 80 micrometers on the abcissa.

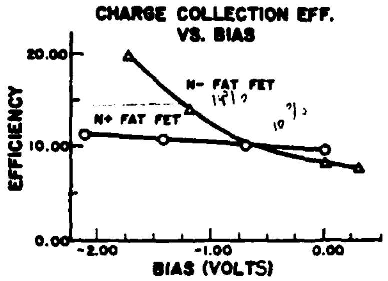

Fig. 3. Charge collection efficiency versus bias voltage for fat FET test structures with N- and N+ implants.

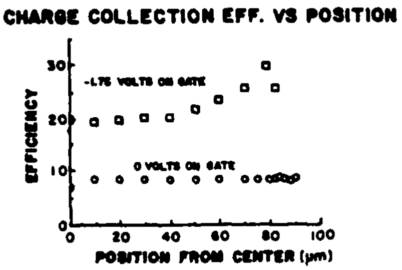

Fig. 4. Collection efficiency *versus position in* micrometers along the length under the gate of a Fat FET test structure with the N- implant and either zero or -1.75 volts bias

GEOMETRY OF THE SENSITIVE VOLUME

The collection efficiency data of Figs. 2-4 can be used to obtain rough estimates of the dimensions of the sensitive volume for the Rockwell Fat FET structures within which any charge generated should be collected. The lateral dimensions are easiest since the regions of enhancement extend roughly 10 micrometers beyond each edge. According to Fig. 3, the thickness of the sensitive volume will depend on bias for the N- implant but not for the N+ implant. This is consistent with the fact that the width or thickness of the depletion region should exhibit far greater increases with bias for the lower density N- implant than for the higher density N+ implant. At zero bias the thickness of the depletion region for both shouldn't extend much beyond 0.1 to 0.2 micrometers. Yet the data of Figs 2 and 4 suggest that even for what should be thin depletion regions in test structures with either the N+ implant or the N- implant at low bias, at least 10 percent of the charge generated along the entire trajectory of the 1.6 MeV helium ions is collected. Most of this is presumably due to charges generated outside the depletion region reaching the depletion region by diffusion or drift.

The thickness of any part of the sensitive volume can be estimated from the charge collected at that location by calculating the fraction F of the helium ions incident energy that is deposited in the sensitive volume, assuming that all charge generated flip-flops but if it is due to diffusion of charge during the relatively long integration time of the PHA circuits, the contribution to SEUs would be much less. One would expect the relative contribution of edge effects to be greater as the devices are scaled down. Figure 7. repeats the calculation assuming the dimensions of the sensitive region have been reduced to 1 x 50 micrometers but the edge regions are assumed to extend the same distance beyond the lateral dimensions of the smaller gate as they did for the larger Fat FET. While these reduced dimensions are still larger along one side than a circuit FET, the edge effects already dominate the energy-deposition spectra. Of course, it is not realistic to expect the enhanced charge collection at the edge of the small FET gate to extend as far as for the the Fat-FET test structure but the conclusion that a considerable enhancement of charge collection is to be expected over that predicted without including edge effects is probably justified.

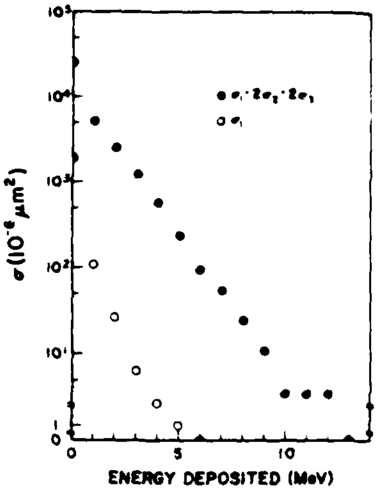

Fig. 7. Same integral energy-deposition spectra calculated for a test structure in which the lateral dimensions of the central region of the device have been reduced to 1 x 50 micrometers but the edges of enhanced charge collection extend beyond in the same manner as in Fig. 5.

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Appendix C

METHODS FOR CALCULATING SEU RATES FOR BIPOLAR AND NMOS CIRCUITS

P. J. McNulty, W. G. Abdel-Kader, and J. M. Bisgrove
Physics Department
Clarkson University
Potsdam, New York 13676

ABSTRACT

Computer codes developed at Clarkson for simulating charge generation by proton-induced nuclear reactions in well-defined silicon microstructures can be used to calculate SEU rates for specific devices when the critical charge and the dimensions of all SEU sensitive junctions on the device are known, provided one can estimate the contribution from externally-generated charge which enters the sensitive junction by drift and diffusion. Calculations for two important bipolar devices, the AMD 2901B bit slice and the Fairchild 93L422 RAM, for which the dimensions of the sensitive volumes were estimated from available heavy-ion test data, have been found to be in agreement with experimental data. Circuit data for the Intel 2164A, an alpha sensitive dRAM, was provided by the manufacturer. Calculations based on crude assumptions regarding which nuclear recoils and which alphas trigger upsets in the 2164A were found to agree with experimental data.

INTRODUCTION

Single-event upsets (SEUs) experienced by circuits traversing the inner radiation belts are primarily the result of nuclear reactions induced by protons trapped in the belts (1,2). In order to perform reliable calculations of SEU rates for specific devices, one must have a detailed knowledge of the natural proton environment, the ability to predict the pattern of charge generated by nuclear reactions as a function of incident proton energy, and, for each of the SEU sensitive junctions on the device, the dimensions of the junction and the critical charge that must be collected across that junction to trigger an upset. This paper describes how codes developed in our laboratory to predict charge generation in microstructures have been combined with simple assumptions regarding circuit response to calculate SEU rates in two different device types. The Intel 2164A was selected for calculations because both the required circuit information and consistent proton SEU cross section data is available (3). The 2901B bit slice was chosen because, in addition to proton data (4), heavy-ion SEU cross section measurements on the memory registers are available (5) which could be used to estimate critical charges and cross sectional areas for the sensitive junctions on the device, and the presence of a buried layer defines the thickness of the associated sensitive volume. The heavy-ion data available for the 93L422 (6) is less complete but good proton data exists (6). Upsets in the 2901B and the 93L422 bipolar devices have proven to be an important problem for many satellite systems.

CLARKSON SIMULATION CODES

Codes have been developed at Clarkson by Farrell and McNulty (7,8) which simulate the nuclear reaction and calculate the energy deposition within parallelepipeds surrounding or close to the interaction. They are Monte-Carlo programs which choose the energy and trajectory of the incident proton according to the environment or accelerator exposure being simulated, randomize the locations of any nuclear reactions according to the inelastic cross section, and follow the standard cascade and evaporation models in choosing the identity, energy, and direction of secondary particles emerging from the cascade and evaporation stages of the interaction. For details of the nuclear physics behind the codes see Refs. 7-9 and especially Ref. 10. The computer follows each secondary particle to determine whether it intersects the sensitive volume defined by a parallelepiped as shown in Fig. 1. It then calculates the energy deposited in the sensitive volume by all the intersecting charged particles. The energy deposited can be converted to charge generated by dividing by 22 MeV/pC.

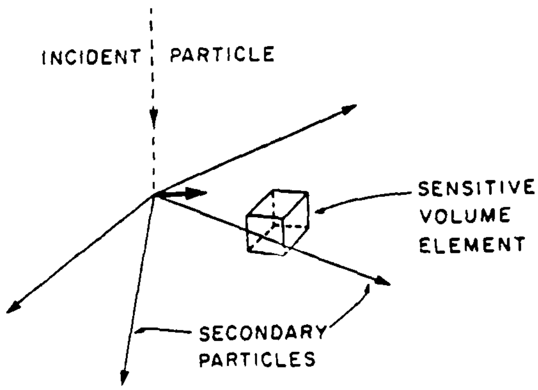

Fig. 1 Schematic of nuclear reaction relative to sensitive volume.

The codes have been tested extensively in silicon by comparison with pulse-height spectra of the charge collected in nuclear solid-state detectors with detector thicknesses ranging from 2 μm to 97 μm exposed in air to protons having incident energies ranging from 27 to 158 MeV. The codes are found to give good fits to the experimental data (7, 11). A typical comparison of simulated and measured integrated pulse-height spectra is shown for 125 MeV protons incident on a 2.5 micron thick detector in Fig. 2.

*Supported in part by AFGL and the DNA-DARPA SEU program.

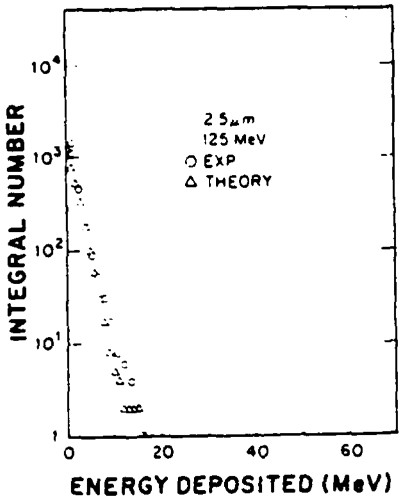

Fig. 2 Comparison of thoretical calculations of the number of events in which more than a certain energy is deposited versus that value of the energy deposited.

User inputs include the number of protons incident on the exposed area, their energy spectra, and their angular distribution. Monoenergetic unidirectional beams arriving at normal incidence to the chip were used in all the comparisons with accelerator data described below. The user must also specify the dimensions of the larger parallelepiped in which nuclear reactions may be initiated and the location and dimensions of the smaller parallelepiped representing the sensitive volume within which the energy deposition is to be calculated.

Figure 3 compares the simulated energy deposition for the same small sensitive volume embedded in different thicknesses of surround. Significant contributions to the integrated energy-deposition spectra appear to only come from interactions that occur within 10 μm of the sensitive volume except at very small energy depositions. Low energy depositions are dominated by traversals of the sensitive volume by alphas and other light secondaries as evidenced by a sharp increase in events. This is consistent with our earlier conclusion that the recoiling nuclear fragment is the primary means of generating sufficient charge to generate an SEU in circuits that are insensitive to alphas (12). For circuits not sensitive to alpha strikes, the calculations can be shortened considerably by only considering nuclear interactions that occur within 10 μm or so of the sensitive volume (3).

BIPOLAR CIRCUITS

The AMD 2901B has been the subject of thorough studies of its SEU response to both protons and heavy ions at JPL. Zoutendyk, et al. (5) have shown that the 2901B exhibits different SEU cross sections depending upon whether the circuit element is being addressed during the exposure. Since only data for the unaddressed mode exist for both heavy ions and protons, we limit ourselves to this mode in what follows.

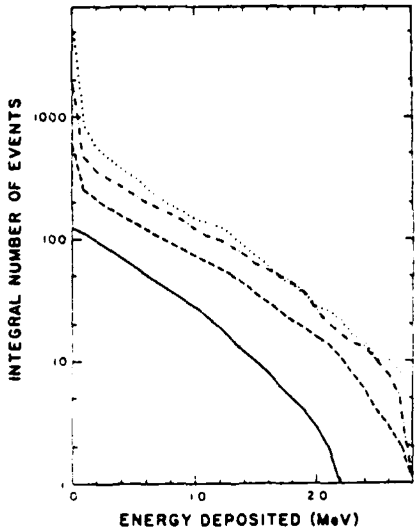

Fig. 3 Comparison of the simulated spectra of events in which more than a certain energy is deposited in a 1 μm cube of silicon embedded in different thicknesses of silicon surround but exposed to the same fluence of protons. Nuclear reactions can occur anywhere in the larger volume. Curves are drawn for external cubical volumes of 1 μm (solid), 2 μm (dashed), 4 μm (dot-dash), and 8 μm (dot).

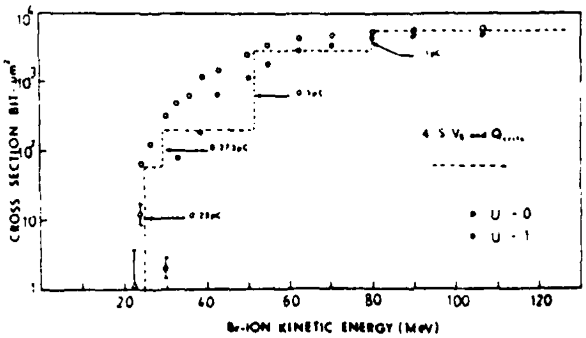

Fig. 4 SEU cross section versus kinetic energy of the incident bromine ion. Taken from Ref. 5. Dashed lines represent our attempt to fit their data by four sensitive volumes.

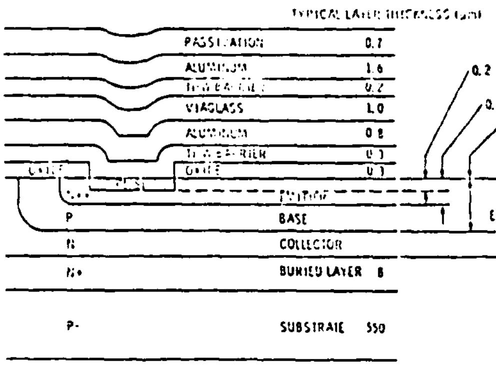

Fig. 5 Schematic taken from Ref. 5 showing the thicknesses of the layers of a 2901B circuit element.

The SEU cross sections measured by Zoutendyk, et al. (5) are plotted as circles in Fig. 4 versus the energy of the incident bromine ion. Figure 5 is a schematic of the 2901B showing the thicknesses of the various layers of a circuit element. According to Ref. 5, the collected charge is the charge generated in the silicon layer between the level of the base-emitter junction and the top of the buried layer, a distance of 3um. Using the recipe and Figs. 6 and 7 from Ref. 5, the charge generated in this layer can be calculated for any bromine energy.

The dashed lines in Fig. 4 attempt to represent their measured cross sections by the lateral dimensions of four sensitive volumes - each having different critical charges. The cross sectional areas of the four volumes can be obtained from the ordinate of Fig. 4 and the critical charges can determined from the abscissa. The thickness of all four are 3um. The critical charges determined for the four equivalent structures are given in Fig. 4 with arrows pointing to their corresponding thresholds. The presence of the buried layer presumably terminates any charge that might otherwise enter the sensitive volume by drift or diffusion from deeper in the substrate. The fact that the four sensitive volumes are nested must be taken into account in the proton calculations.

Calculations

The Clarkson codes were used to simulate the pulse-height spectra for exposure of the four sensitive volumes to protons incident at the three energies for which JPL proton data exist for the 2901B (4). The cross-sectional areas that were obtained from Fig. 4 and used for these calculations are given in column 2 of Table 1. Column 1 represents the range of energy depositions in the 3 μm sensitive layer between threshold for that sensitive volume and threshold for the next larger one. Since the sensitive volumes are nested, the proton cross section for upsets at a given proton energy is taken to be the sum of the cross sections for depositing an energy between the threshold for that volume and the threshold for the next larger. These values are listed in Table 1.

Table 1 (2901B)

E_{th} (MeV)	Cross Section(μm^2) Per Bit	Proton Energy (MeV)		
		56	130	590
3.5 — 5.9	60	2.8 10^{-12}	1.2 10^{-11}	1.5 10^{-11}
6.0 — 10.9	120	2.05 10^{-11}	1.21 10^{-10}	1.88 10^{-10}
11.0 — 21.9	3000	—	8.8 10^{-11}	5.56 10^{-10}
≥ 22	5000	—	—	7.6 10^{-11}
SEU CROSS SECTION(cm^2) / DEVICE		2.33 10^{-11}	2.21 10^{-10}	8.35 10^{-10}

Comparison between these calculated values and the experimental proton measurements on the 2901B taken from Ref. 4 is shown in Fig. 6. Circles represent simulated cross sections from this paper and the dashed curve connects the experimentally measured values at the same incident energies. The fit is excellent at the lower proton energies and reasonably good even at the highest energy.

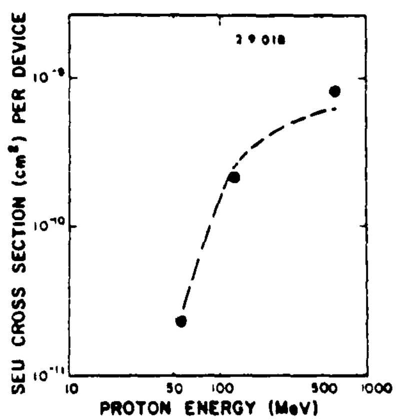

Fig. 6 Comparison of calculated SEU cross sections (circles) with measurements at the same incident proton energies for the 2901B. Dashed curve connects experimental points from Ref. 4.

A second bipolar device for which JPL heavy-ion and proton data exist is the FSC 93L422 RAM. Reference 6 reports a single measured threshold LET of 1.8 MeV cm^2 /mg and a flat SEU cross section of 2000 μm^2 for ions having higher LETs. The sensitive volumes are arbitrarily assumed to have a thickness of 15 μm. A normally-incident particle with this threshold LET would deposit 6.2 MeV in a 15 μm layer of silicon. The Clarkson proton codes were used to calculate the cross section for depositing more than 6.2 MeV in a sensitive volume with lateral dimensions given by the SEU heavy-ion cross section and a thickness of 15 μm. Our calculations were not particularly sensitive to the thickness chosen for the sensitive volume. Figure 7 shows a comparison of our simulated cross sections (circles) calculated at a number of incident proton energies with the curve reported in Ref. 6 to best fit the JPL measured values. Again the agreement is excellent.

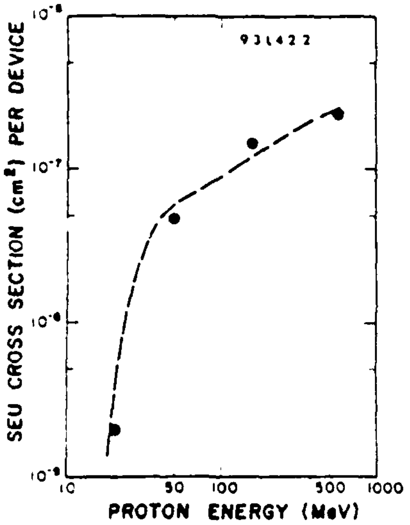

Fig. 7 Comparison of calculated SEU cross sections (circles) with with the best-fit curve from Ref. 6 for their 93L422 proton data.

NMOS DRAM

We assumed that SEUs in the Intel 2164A dRAM result from collecting a sufficient number of electrons to exceed the critical charge required for an error, 149 fC or 3.3 MeV. The lateral dimensions of the sensitive volume were taken to be those of the memory cell 3.5 μm x 16.5 μm and the thickness taken to be that of the depletion region under the node, 0.18 μm.

The collection of charge generated outside this sensitive volume through drift and diffusion must be considered. As a first attempt, we assumed that all recoiling residual nuclear fragments that traverse the sensitive volume trigger an upset if the recoil had a total kinetic energy equal to or greater than 3.3 MeV, i.e., we assumed all the charges generated in the short recoils were collected through field-assisted drift. The number of such intersecting recoils resulting from simulated exposures to given fluences of protons are listed in row 5 of Table 2 for five different proton energies. The corresponding SEU cross sections for a 64K memory with alternating locations filled with ones and zeros are given in row 6.

The 2164A can be upset by alphas but the large critical charge suggest that only alphas that traverse the sensitive volume near the end of their range will trigger an upset. The high ionization levels needed to maintain field assisted drift along the trajectory are more likely to occur near the end of the track. The numbers of alphas in these simulations to emerge from nuclear reactions and strike the sensitive volume during the last 5 μm of its range are given in row 7 of Table 2 with the corresponding SEU cross sections per device given in row 8. The total proton cross section, i.e., the sum of the cross sections for recoil-induced and alpha-induced errors is given in the bottom row of Table 2.

Table 2 (Intel 2164A)

Proton Energy (MeV)	21	41	82	124	155
No of Incident Protons ($\times 10^8$)	4.863	5.775	3.5	4.875	5.52
Fluence ($\times 10^{13}$ cm^{-2})	6.107	7.233	4.4	6.123	6.93
No. of Recoils Intersecting The Sensitive Volume (S.V)	168	297	242	324	367
No of Intersecting Recoils > 3.3 MeV	0	22	58	94	110
σ_r Device ($\times 10^{-8}$ cm^2)	0	0.978	4.17	4.9	5.07
No of Alphas Intersecting The S.V (Ender)	5	162	117	192	246
σ_α Device ($\times 10^{-8}$ cm^2)	0.26	7.14	8.49	10.035	11.36
$\sigma_r + \sigma_\alpha$ ($\times 10^{-7}$ cm^2)	0.026	0.81	1.27	1.49	1.64

Experimental measurements to be described elsewhere (3) have been carried out at the same incident proton energies as used in the simulations. The advantage of these measurements over the earlier measurements on dRAMS (12,13) is that the 2164A, a part designed for military applications, exhibits far less variation in SEU cross section among devices than was true for those earlier commercial parts. The measured values presented below are averages of the cross sections measured for five parts where each measurement included over 100 errors. Figure 8 compares theory and experiment. The dashed lines connect points that represent the average measured cross section and the circles represent the simulated cross sections. The agreement is quite good except at 21 MeV. It is interesting to note that reducing the critical charge by about a factor of 2 would bring the 21 MeV calculation into agreement without changing the other points significantly. Perhaps including the charge collected through thermal leakage between refreshes would improve the fit.

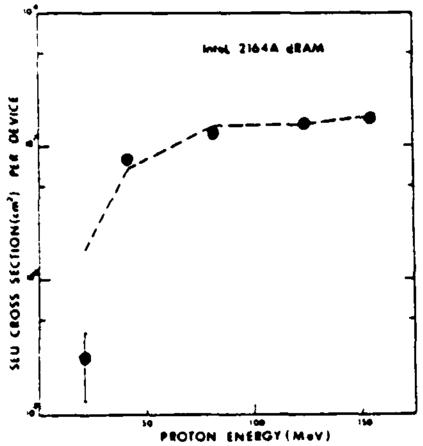

Fig. 8 Comparison of SEU cross sections obtained from simulations with measured values obtained at the same incident proton energies. The dashed curve connects points representing the average cross sections for five devices from Ref. 3.

CONCLUSIONS

The Clarkson codes developed for simulating charge generation pulse-height spectra can be used to calculate SEU cross sections for some devices with relatively simple assumptions. Further studies are needed to determine the extent to which the technique can be generalized. In particular, the dRAM calculations described above involve crude assumptions that may not work for circuits with smaller feature size and smaller critical charges. However, it is hoped that combining our codes with some of the sophisticated circuit models being developed by others will lead to comparable success for those devices which are not susceptible to the kind of simple assumptions attempted here.

The agreement found for the bipolar devices demonstrates that, for alpha insensitive devices, proton-induced upsets are primarily the result of the recoiling nuclear fragment and that heavy-ion data may be useful in predicting proton response and vice-versa. However, the short range of the nuclear recoil in proton interactions must be taken into account in making such correlations.

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