This paper describes new software simulation code for predicting single event upset data from measured heavy ion data, using methods, code, and algorithms already reported in the open literature. The measured data that is used to compare against the results of this new simulation code has also been reported in the open literature (R. Koga, et al). The new code is not provided as part of this paper, only the methodology used in generating the code. This paper presents results of basic research, not design-to information, and is representative of other papers reported in the open literature (see paper references). Therefore, the content of this paper is suitable for being made publicly available at the IEEE conference and the resulting IEEE journal.

Monte-Carlo Simulation of Proton Upsets in Xilinx Virtex-II FPGA Using a Position Dependent Q_{crit} with PROPSET

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35-WORD ABSTRACT:

Proton upsets, predicted by the software code, PROPSET, for Xilinx Virtex-II FPGA are presented. PROPSET uses heavy-ion upset data to determine the upset energy threshold at each position within the device's sensitive volume.

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INTRODUCTION

An upset in an element of a semiconductor microelectronic device occurs when a charged particle passing through a sensitive volume (SV) of the device creates a charge in the SV greater than the critical charge (Q_c) necessary to change the state of the element. Charged particles lose energy as they pass through material by interaction with electrons and, very rarely, through scattering from or reactions with nuclei in the material. In the semi-conductor Silicon, it takes 3.6 eV to form one electron hole pair, therefore, the charge created is related to the energy deposited by the charged particle so that, $Q_c = E_c/22.5$, where the critical energy, E_c, is in MeV and Q_c is in pico-Coulombs.

The linear rate of energy transfer, (dE/dx), where dE is the energy deposited by a particle in traveling a distance dx, is called the Linear Energy Transfer (LET). It is usually divided by the density of the material so that the LET has units of MeV-cm^2/mg. LET depends on the square of the charge of the particle and is a double valued function of the energy of the particle. That is there are two particle energies for a given charged particle corresponding to each LET. As a result, particles with the same charge and LET may have very different energies. The distance a charged particle may travel in a material, the range of the particle in the material, is dependent on the energy of the particle, so that the same charged particle with higher energy will travel farther, i.e. the range is longer. For example, an aluminum particle with an energy of 15 MeV (0.58 MeV/nucleon) has a LET of 12.3 MeV-cm^2/mg and a range of 7.27 microns, while one with an energy of 30 MeV (1.15 MeV/nucleon) has a LET of 12.3 MeV-cm^2/mg as well, but a range of 12.44 microns.

These differences are of no concern for heavy ion testing for which both the energy and the LET of the incident heavy charged particles are known. This makes it meaningful to present heavy ion single event upset data as a function of LET as is usually done.

However, the situation is different for proton induced single event upsets. Incident protons do not transfer enough energy by direct interaction with electrons in a semi-conductor to cause upsets except in a few very sensitive devices. Proton induced upsets are produced by the energy deposited in a SV of a device by the heavy ions (secondary particles) created in nuclear scattering and reactions that occur throughout the SV and surrounding material. The proton upset cross-section, for an incident proton energy, is a complex function of the position at which a nuclear process occurs, the secondary particles produced in the process and the energies and directions of the secondary particles. Due to the complexity of this process, it is impossible, from a proton induced upset measurement, to know the LETs of the secondary particles causing upsets. Therefore, proton induced upset cross-sections are presented as a function of incident proton energy rather than LET.

Since it is the creation of charge greater than Q_c in a device SV by the energy deposited through the slowing of heavy ions passing through the SV that cause upsets in both the proton case (secondary heavy ions) and the heavy ion case, efforts have been made to predict proton induced SEU cross-sections from measured heavy ion SEU cross-sections. If this can be done reliably, the need for proton testing would be lessened.

Monte Carlo nuclear reaction and scattering codes may be used to calculate proton induced SEU cross-sections. They track all the secondary particles from nuclear interactions and compute the LET and energy deposited by each particle along its path. But this is not sufficient because some information about the part geometry and upset sensitivity must also be included. In a recent paper Petersen et al. [5], showed that the upset rate could be considered as dependent on the location, within a rectangular parallelepiped (RPP) of constant thickness, of the point of energy deposition within the sensitive volume. They also showed that the sensitivity to upset of a bit in a device is represented in the Weibull [9]or log normal function derived from fitting measured heavy ion upset versus LET distributions.

The Monte Carlo internuclear cascade/evaporation simulation code, PROPSET, has been developed to incorporate the Petersen et al. method of predicting proton induced SEU cross-sections using heavy ion data. As a test case for PROPSET, the heavy ion and proton cross-section data of Koga et al. [1] for the Xilinx Virtex-II FPGA will be used.

In the following sections, the PROPSET code will be described and predicted proton induced upset cross-sections will be compared with the measured data and with results of the Edmunds [2], PROFIT [3], and earlier Petersen [4] models for simulating proton induced cross-sections from heavy ion data for the Virtex-II FPGA as presented in the Koga et al. [1] paper. Sensitivity of the predicted cross-sections to Weibull parameters, to variation of the thickness of the SV and to variation of the length to volume ratio of the SV is also explored.

THE CODE

PROPSET is a new Monte Carlo simulation code developed to predict proton induced single event upset cross-sections from measured heavy ion data using the position-dependent energy deposition threshold method suggested by Petersen et al. [5]. The nuclear physics part of the code includes a cascade stage followed by an evaporation stage. The CLUST code [6], which is based on the work of Bertini (ref), is used for the cascade stage and the EVAP code, which is based on an algorithm by Tang [7], is used for the evaporation stage as described by O'Neill et al. [8].

Inputs to PROPSET are: the incident proton energy (Ep) in MeV; the thickness (t) of sensitive volume in microns; the saturation cross-section (σ_{sat}) in cm^2; the LET threshold, (L_0) in MeV- cm^2/mg; and the dimensionless parameters s and W. The parameters $L_{0,}$ σ_{sat}, s and W are determined from fitting heavy ion cross-section, σ, versus LET, L, data, with the usual Weibull [9] formula: $\sigma = \sigma_{sat}$ (1- exp (-((L-L_0)/W)^s)), which defines s and W.

PROPSET defines the sensitive volume as a rectangular parallelepiped, RPP, of volume, t(σ_{sat}) = t(L_x)(W_y), where L_x is the length and W_y is the width of the SV. Normally the ratio (L_x/W_y) =1, however, PROPSET allows the ratio to be varied while keeping the area constant. A slab of bulk silicon containing the SV is usually defined by adding 10 microns to the length, 10 microns to the width, 5 microns to the top and 2 microns to the bottom of the SV. The amount of bulk silicon surrounding the SV is chosen to be reasonably small to minimize calculation time, but can be readily changed in PROPSET. The protons enter the slab normal to the top surface.

Once the slab volume is defined, it is divided into 100,000 cells. Next, one of the cells and a point within that cell are chosen randomly. Then, using the CLUST/EVAP code, a nuclear reaction is generated at that point. Each fragment or recoil particle produced in this reaction is tracked as it moves through the slab in small steps, Δr. The energy deposited in the slab in each step is calculated and a new energy of the particle is determined. A test on the direction of travel of a particle terminates tracking of those particles whose path can not pass through the SV.

PROPSET divides the SV into a number (N) of RPP sub-volumes of thickness (t) and areas A(I) = ((σ_{sat})/N)I, where $1 \leq I \leq N$. These sub-volumes are each centered about the center of the SV. As each fragment from a nuclear event that passes through the SV is tracked, the energy deposited by that fragment at each small step is added to the energy deposited in each sub-volume that it passes through by all previous steps in that sub-volume and to the energy deposited in that sub-volume by any other fragments from the nuclear event until all fragments from this event that enter the SV have either stopped in the SV or exited it. For the nuclear event, this results in an energy deposition (E(I)) associated with each sub-volume area (A(I)). An energy deposition threshold $(E_c)_I$ is determined for each A(I) from

$$(E_c)_I = L_I \times t \qquad 1)$$

where

$$L_I = W((-\ln(1-(A_I/\sigma_{sat}))^{1/s}) + L_0 \qquad 2)$$

and L_0, s, W and σ_{sat} are the Weibull parameters determined from heavy ion data and L_I is the LET associated with the area A_I through the Weibull parametrization. When the energy deposited in a sub-volume (E_I) exceeds $(E_c)_I$, a SEU is counted, tracking of that particle is terminated and a nuclear event at a new randomly chosen location generated. In order to speed the calculation, the same nuclear reaction is used at 1000 randomly chosen sites before a new nuclear event is generated. This process is repeated many times, the number of SEUs tallied and the SEU cross-section per bit calculated from the ratio of the number of SEUs to the number of incident protons/cm^2, the fluence. The simulated device cross-section and number of SEUs per device in a typical test are then readily calculated. It takes about 20 minutes to run a PROPSET simulation for a typical part at a single proton energy on a laptop running at 700 megahertz.

Results for the Xilinx Virtex II FPGA

PROPSET was used to simulate the proton induced upset cross-sections for the configuration memory and block RAM of the Xilinx Virtex-II FPGA using the heavy ion data and Weibull parameters of Koga et al. [1] and comparisons made to the measured proton cross-sections presented in that paper. Fig. 1 shows the PROPSET calculation of the upset cross-sections at several incident proton energies for the Virtex-II configuration memory compared to the measured cross-sections. Also shown are the predictions using the Edmonds, PROFIT and earlier Petersen models as presented and described by Koga et al. [1]. Fig. 2 is a similar plot for the Virtex-II block RAM. As can be seen from Fig. 1 and Fig. 2, the PROPSET cross-sections are very close to the measured data and the upper-limit prediction of the Edmonds model for energies above about 70 MeV. They fall below the measured values at the lower energies where the CLUST code is expected to be less accurate and where elastic scattering of protons, which is not yet included in PROPSET, may contribute.

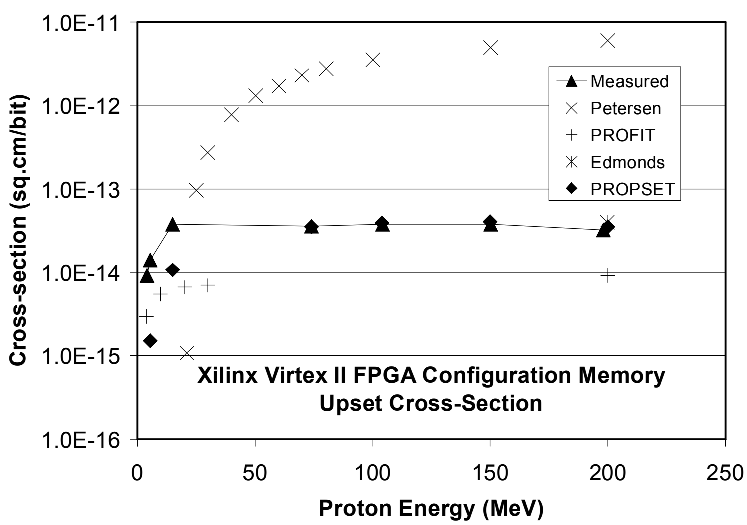

Figure 1: Comparison of proton induced SEU cross-sections for the Xilinx Virtex-II FPGA configuration memory predicted by PROPSET and other models, with measured cross-sections.

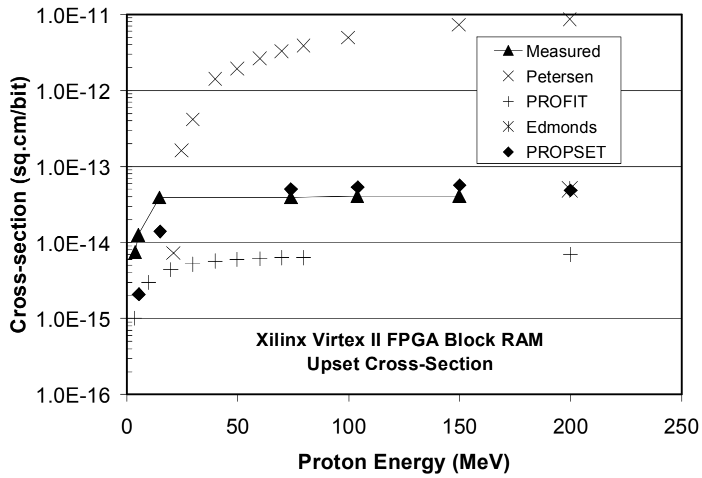

Fig. 2: Comparison of proton induced SEU cross-sections, for the Xilinx Virtex-II FPGA Block RAM, which were predicted by PROPSET and other models, with measured cross-sections.

Sensitivity to Sensitive Volume Thickness and Shape

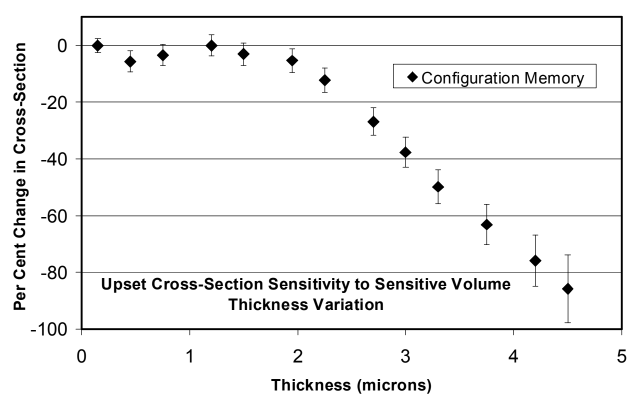

Fig. 3: Percent change in the PROPSET calculated SEU cross-section for the Xilinx Virtex II FPGA Configuration Memory when the thickness of the sensitive volume is increased from 0.15 to 4.5 microns (a factor of 30). The length to width ratio of the SV was 1 to 1. The cross-section is constant until about 2 microns after which it decreases linearly with increasing thickness. Errors bars are statistical only.

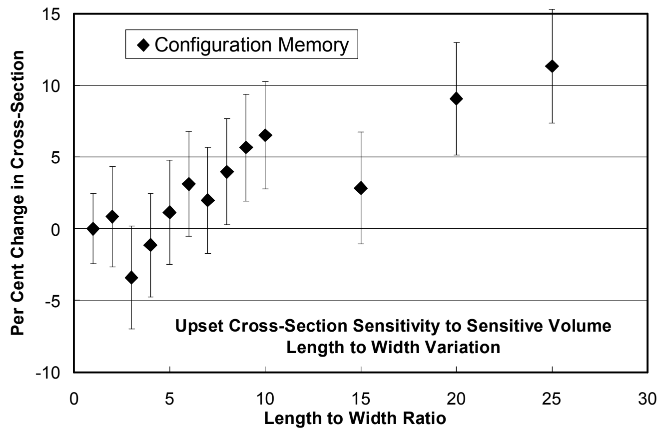

Fig. 4: Percent change in the PROPSET calculated SEU cross-section for the Xilinx Virtex-II FPGA Configuration Memory induced by 200 MeV protons as the length to width ratio of the sensitive volume is changed from 1 to 25. The volume and thickness of the SV was constant. The maximum change was less than 15 percent. Errors bars are statistical only.

Fig. 3 is a plot of the percent variation in the PROPSET calculated SEU cross-section for the Virtex-II FPGA induced by 200 MeV incident protons as the thickness of the SV is changed by a factor of 30 from 0.15 to 4.5 microns with a constant length to width ratio of 1. The change in cross-section is constant until the thickness is increased to about 2 microns and then decreases with increasing thickness linearly. This decrease is a result of the increase of the energy deposition threshold with increasing thickness (see equation 1). In the region of thicknesses from 0.15 to 2 microns, the cross-section remains constant as the energy deposit threshold increases with thickness because an increased number of events may occur in the larger sensitive volume and increased energy is deposited by secondary fragments along longer tracks in the larger sensitive volume. Fig. 4 is a plot of the percent variation in the PROPSET calculated SEU cross-section for the Virtex-II FPGA configuration memory which is induced by 200 MeV incident protons as the length to width ratio of the SV is changed by a factor of 25 while the volume and thickness of the SV is unchanged. The upset cross-section is seen to change by less than 15 percent. The PROPSET calculated cross-section for this part is insensitive to variation of the length to width ratio of the sensitive volume.

Sensitivity to Weibull Parameters

In order to explore the sensitivity of proton induced upset cross-sections predicted by PROPSET to the Weibull parameterizations obtained by fitting measured heavy ion data, heavy ion data for the Xilinx Virtex-II FPGA Block RAM and for the Texas Instruments SMJ44100 4 meg DRAM were fit using the SOLVER capability of MicroSoft Excel to minimize a goodness of fit parameter by varying the values s and W in the standard Weibull formula and by a "linear Weibull" technique. Plotted in the appropriate way, $\ln[\ln(1/(\sigma/ \sigma_{sat},))]$ on the y axis and $\ln(L- L_0)$ on the x axis, data, that may be represented by a Weibull function, may be fit with a straight line, y=mx+b, where the Weibull parameter, s, is equal to the slope of the line, m, and the Weibull parameter, W, may be calculated from W=exp(-b/s), where b is the y intercept of the straight line. When measured data are plotted in this way, deviations from linearity which may come from difficult-to-measure low cross-section points at low LET, from the presence of more than one upset process or some other reason may be observed. Figure 5 shows the heavy ion data for the Virtex II FPGA Block RAM on a linearized plot with straight line fits for all the data and for only the high LET data. The equations of the straight lines, as well as the standard R^2 goodness of fit parameters, are shown on Figure 5. Weibull parameters for the Xilinx Virtex II FPGA Block Ram and for the SMJ44100 obtained by various fitting techniques are shown in Table 1.

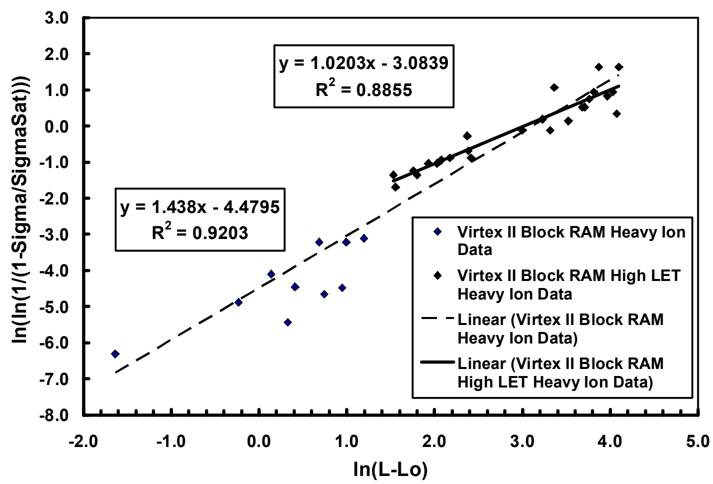

Figure 5: Linearized plot of Xilinx Virtex II FPGA heavy ion cross-section data. A straight line fit to all the data is shown as the dashed line. Since the low LET data seems to have more scatter and a different slope from the high LET data, a separate linear fit to that data is shown as the solid line.

Table 1. Weibull Parameters used in the sensitivity to Weibull study.

Part #	Part ID	# Bits	L0 (MeV CM^2/MG)	Device (CM^2/Bit)	W	S	Thickness Microns
25	Xilinx VII FPGA_Blk_RAM						
	Koga Weibull	7.40E+05	1	4.19E-08	17.0	0.90	0.15
	Excel Solver Weibull	7.40E+05	1	4.19E-08	21.8	1.05	0.15
	Linear Fitted Weibull	7.40E+05	1	4.19E-08	22.5	1.44	0.15
	High LET Linear Fitted Weibull	7.40E+05	1	4.19E-08	20.5	1.02	0.15
6	SMJ44100*						
	Calvel Weibull	4.20E+06	1.39	4.76E-07	15.0	1.21	1.0
	Excel Solver Weibull	4.20E+06	0.28	4.76E-07	75	0.35	1.0
	Linear Fitted Weibull	4.20E+06	0.28	4.76E-07	45.8	1.19	1.0
	High LET Linear Fitted Weibull	4.20E+06	0.28	4.76E-07	52.5	0.64	1.0

* # Bits for protons is 2.5E06

The quality of the agreement of the heavy ion cross-sections calculated with Weibull parameters from the various fitting methods (see Table 1.) with the measured data is seen in Figure 6. Koga et al (ref) adjusted their parameters to give cross sections larger than nearly all the measured cross-sections apparently to get a more conservative parameterization of the data. All the methods appear to agree reasonably well with the measured data of this extensive data set although significant differences are seen in the knee of the curves.

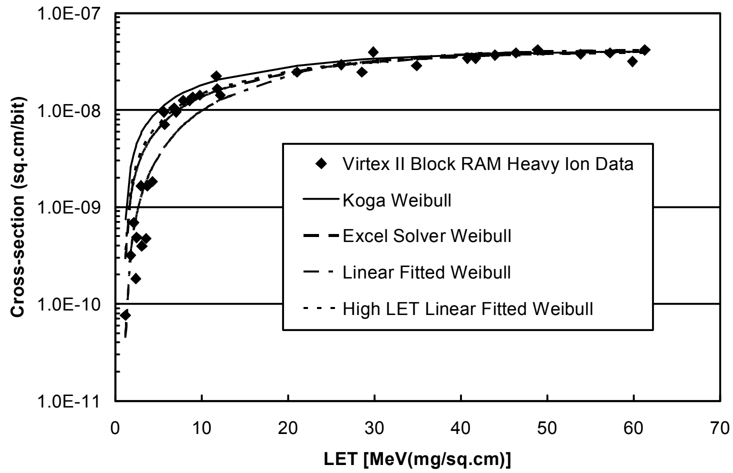

Figure 6: Comparison of Weibull curves calculated with parameters generated from the measured heavy ion data by different fitting techniques with the data for the Xilinx Virtex II FPGA Block RAM (ref). For the solid curve the published Weibull parameters of Koga et al (ref) were used. For the long dash, long dash-short dash, and short dash curves, the Excel Solver, linear fit to all data and linear fit to only high LET data Weibull parameters, respectively, were used. The measured heavy ion data of Koga et al (ref) is shown as diamonds. Values of the Weibull parameters used are in Table 1.

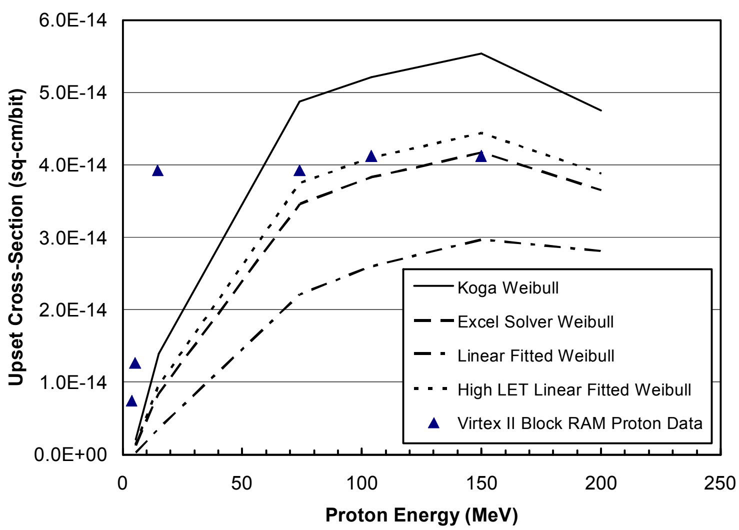

Figure 7: Plot of the PROPSET calculated proton induced SEU cross-section as a function of incident proton energy for Weibull parameters generated from the measured heavy ion data by different fitting techniques. For the solid curve the published Weibull parameters of Koga et al (ref) were used. For the long dash, long dash-short dash, and short dash curves, the Excel Solver, linear fit to all data and linear fit to only high LET data Weibull parameters, respectively, were used. The measured proton data of Koga et al (ref) is shown as triangles.

In Figure 7, proton induced SEU cross-sections calculated with PROPSET for several proton energies and using Weibull parameters obtained by the use of several fitting techniques are compared to the measured proton data of Koga et al (ref). The nominal thickness of 0.15 micron and a length to width ratio of 1 to 1 for the sensitive volume was used. The Excel Solver and the high LET linear Weibull agree well with the measured cross-sections above 70 MeV incident proton energy. There is nearly a factor of two difference between the lowest and the highest cross-section curves shown in Figure 7. For this large set of heavy ion data it is evident that Weibull parameter variations from different fitting methods contribute less than a factor of two to the uncertainty in the proton induced upset cross-sections predicted by PROPSET and much less when the Excel Solver and High LET Linear techniques are used.

In order to explore the sensitivity to Weibull parameter fitting of a part with a less extensive but more typical heavy ion cross-section data set, a similar study was performed on the Texas Instruments SMJ44100 4 meg DRAM (ref). Heavy ion cross-sections at seven LET values in the range from 1 to 55 MeV-cm^2/mg were fit with the Excel Solver, Linear Weibull and High LET Linear Weibull methods. The nominal thickness of 1 micron and a length to width ratio of 1 to 1 were used. Figure 8 compares the PROPSET calculated proton induced cross-sections for the SMJ44100 at several proton energies with the measured data. The calculated proton induced cross-sections are seen to be sensitive to the fitting method and contribute more than a factor of two to the uncertainty in the predicted cross-sections for proton energies above 100 MeV and larger uncertainty in those below 100 MeV.

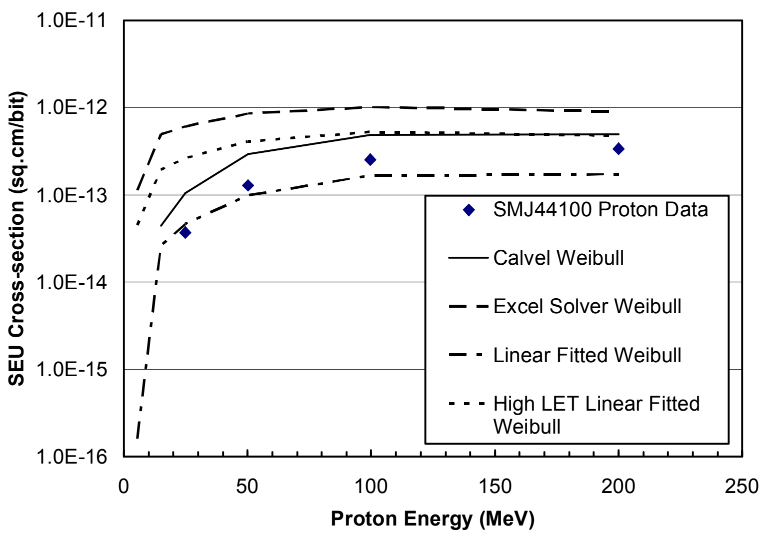

Figure 8: Comparison of proton induced upset cross-sections, for the SMJ44100 4 meg DRAM calculated with PROPSET at several energies and with Weibull parameters determined by fitting the heavy ion data (ref) with the methods described in the body of the paper, with the measured proton data (ref).

Parts Results

PROPSET was used to calculate the upset cross-sections due to incident 200 MeV protons for a number of parts, for which there is both heavy ion and proton data in the literature. Table 1 lists the part numbers (used in this paper), their identifiers, and the number of bits in each device, the

Weibull parameters, the nominal (published) sensitive volume thicknesses and references to papers where the data were published.

Table 2. Parts Information

Part #	Part ID	# Bits	L0 (MeV CM^2/MG)	σ_{sat} (CM^2/Bit)	W	S	Thickness (Microns)
1	93L422_AMD	1.00E+03	0.55	1.50E-05	5.5	0.66	2.0
2	93L422_Fairchild	1.00E+03	0.6	2.60E-05	4.4	0.7	2.0
3	2164	6.40E+04	0.487	1.71E-06	4.95	1.422	2.0
4	1601_Epi	6.40E+04	2.75	6.25E-06	30	1.5	1.0
5	OW62256	2.56E+05	2.9	1.90E-06	14	2.3	1.0
6	SMJ44100*	4.20E+06	1.39	4.76E-07	15	1.21	1.0
7	62256	2.62E+05	1.6	2.44E-06	20	1.65	1.0
8	IBM_16MEG	1.68E+07	1.7	7.74E-09	20	3	0.2
9	MT4C1004C	4.20E+06	1.54	3.09E-07	14.5	1.45	1.0
10	KM41C4000Z-8	4.20E+06	1.52	3.09E-07	18	1.45	1.0
11	01G9274	4.20E+06	1.6	2.30E-08	28	3.25	0.2
12	MT4C4001	4.20E+06	1.49	3.09E-07	20	1.2	1.0
13	HM6116	1.60E+04	4.2	4.12E-06	7.9	2.5	1.0
14	62832H	2.62E+05	3.4	3.80E-07	20	1.5	1.0
15	2901B	80	4.2	3.75E-05	10	1.5	2.0
16	TC514100Z-10	4.20E+06	0.86	5.00E-07	18	1.15	1.0
17	HM_65656	2.62E+05	1.5	4.20E-07	12	1.75	1.0
18	MB814100_10PSZ	4.20E+06	1.15	7.62E-07	15	1.35	1.0
19	HYB514100J-10	4.20E+06	0.86	5.00E-07	14	1.1	1.0
20	LUNA_C	1.68E+07	3.2	8.93E-09	14	3	0.2
21	D424100V-80	4.20E+06	0.8	3.57E-07	10	1.1	1.0
22	PowerPC603_Reg.	3.00E+03	2.29	6.66E-07	10.9	2.5	1.0
23	PowerPC603_Cach	1.42E+05	1.51	2.39E-07	13.5	1.5	1.0
24	HM6516	1.60E+04	5	1.88E-06	14	1.9	1.0
25	Xilinx VII FPGA_Config Mem	2.80E+06	1	4.37E-08	33	0.8	0.15
26	Xilinx VII FPGA_Blk_RAM	7.40E+05	1	4.19E-08	17	0.9	0.15
	* # Bits for protons is 2.5E06						

Table 3 summarizes the results of the calculation of single event upset cross-sections for the parts listed in Table 2 induced by protons with incident energy of 200 MeV. The protons are incident normal to the surface of the device. The area of a bit in a part is taken to be the saturation cross-section, σ_{sat}, from the Weibull parameterization, the surface is taken to be square unless a length to width different from 1 to 1 is specifically stated and the thickness is taken to be the nominal thickness listed in Table 2 unless specifically stated. When the length to width ratio is changed, the area is held constant so that the sensitive volume is unchanged.

Edmonds (ref) has calculated the upper bound for proton induced single event upset cross-sections from heavy ion data based on quite general principles. PROPSET calculated device cross-sections are compared with the upper bound device cross-sections of Edmonds in Table 3 and with the measured cross-sections. Inspection of the Edmonds upper bound to measured data ratio compared to the PROPSET calculated to measured data shows that PROPSET over predicts the upset cross-sections for all parts except parts 1, 2 and 3 for which there are problems with the data as pointed out by Edmonds (ref), page 1720. The amount that PROPSET over predicts the cross-section varies part-by-part in a way similar to the Edmonds upper bound predictions. The cause of the over prediction and variation in the part-to-part over prediction by PROPSET may lie in the uncertainty due to Weibull parameterizations, to uncertainty in the knowledge of the thickness and of length to width ratio of the parts, to details of the cascade-evaporation code or to other factors. As seen above (Figures 7 and 8), variations in Weibull parameters may cause variations of a factor of two or more in PROPSET predicted cross-sections.

PROPSET calculations of the upset cross-sections due to 200 MeV protons were made for each of the parts listed in Table 2 in which the length to width ratio of the area of the sensitive volume was set at 10 to 1 while holding the area constant and using the nominal thickness and Weibull parameters listed in Table 2. The ratio of the 10 to 1 over the 1 to 1 cross-sections for each part is listed in Table 3. Inspection of this ratio shows that for most parts the predicted cross-sections are not very sensitive to the change in length to width ratio of the sensitive volume. However, for parts 8 (IBM_16MEG), 11 (01G9274) and 20(LUNA_C), which are thin parts (0.2 microns thick), the cross-section are reduced by about a factor of 2 when the length to width is changed to 10 to 1. Other thin parts such as the Xilinx Virtex II Configuration Memory (part 25) and Block RAM (part 26), which are 0.15 microns thick, show less than a 10 percent increase in upset cross-section for a L to W of 10 to 1. Lack of knowledge of the shape of the area of the sensitive volume is seen to introduce about a factor of two uncertainty in PROPSET predictions of proton induced upset cross-sections but that use of square areas in PROPSET results in predicted cross-sections that are conservative estimates when used in SEU risk assessment.

PROPSET proton induced upset cross-section calculations are particularly sensitive to uncertainty in the knowledge of the thickness of the sensitive volume since the volume in which energy may be deposited increases linearly with the thickness and as shown in equation 1, the energy deposition threshold increases linearly as well. As the sensitive volume increases, for a constant energy deposition threshold, the number of upsets will increase because more nuclear events can occur in the volume and the possible path lengths for secondary particles to deposit energy while passing through the sensitive volume are increased. As the energy deposition threshold is increased, the number of upsets will decrease. Figure 3 shows that as the thickness is increased a point is reached where the decrease in upsets due to the increase in thickness of the sensitive volume dominates and the upset cross-section decreases monotonically. This occurs above about 2 microns for the Xilinx Virtex II FPGA Configuration Memory as seen in Figure 3.

The monotonic decrease in PROPSET predicted proton cross-section for 200 MeV incident protons with increase of thickness together with the fact that PROPSET over predicts such cross-sections suggest that it is possible to find a thickness for each part for which the PROPSET predicted cross-section equals the measured cross-section. This was done successfully by iteration for all parts except parts 1,2 and 3 which were not done because of the problems with the data for these parts reported by Edmonds (ref). The thicknesses found by this process are listed in Table 3 in the column labeled "PROPSET Fitted Thickness (microns)." On average it takes an increase of the nominal thickness by a factor of about five in a PROPSET calculation to achieve a cross-section for 200 MeV incident protons equal to the measured cross-section. The largest "fitted" thickness found was 9.5 microns for part 18 (MB814100_10PSZ) which had a nominal thickness of 1 micron. The possible interpretation of these "fitted" thicknesses in terms of charge collection depth or contributing depth as defined by Edmonds (ref) is not possible at this time because of uncertainties in the calculated cross-sections from the Weibull parameters, length to width ratios and model physics. However, the results are presented to encourage discussion.

Huhtinen and Faccio (ref) have used the Monte Carlo transport code FLUKA to calculate the probability distributions for depositing, in a 1 micron by 1 micron by 1 micron cubic volume surrounded by silicon, an energy greater than a given energy versus the energy deposited for protons of 200, 60 and 30 MeV incident energies. PROPSET was used to calculate these probability distributions as well. The energy deposition probability distributions calculated with PROPSET and FLUKA are compared in Figures 9. The distribution calculated by PROPSET for 200 MeV incident protons is seen to be higher than that calculated with FLUKA particularly at energy depositions greater that about 0.02 MeV where it is larger by a factor of 2.5. For 60 MeV protons the energy deposition probability distribution calculated by PROPSET is seen to be much closer to that calculated with FLUKA and for 30 MeV protons the two probability curves agree well over the entire energy deposition range. The reason for this incident-proton-energy dependent difference in the energy deposition probability distributions calculated using different Monte Carlo transport codes is not known at this time but is likely a result of differences in implementation of the model physics used in the codes. This uncertainty in the model physics contributes another factor of about 2 to the uncertainty in calculated SEU cross-sections. Additional code comparisons are planned to resolve such physics model uncertainties. In the mean time, the uncertainties due to Weibull parameters, sensitive volume shape and model physics make the prediction of proton induced upset cross-sections from measured heavy ion data with Monte Carlo transport codes uncertain by about an order of magnitude. Since PROPSET predictions of proton induced upsets are close to the upper bound calculated by Edmonds, they result in conservative estimates of the risk of using parts in a radiation environment.

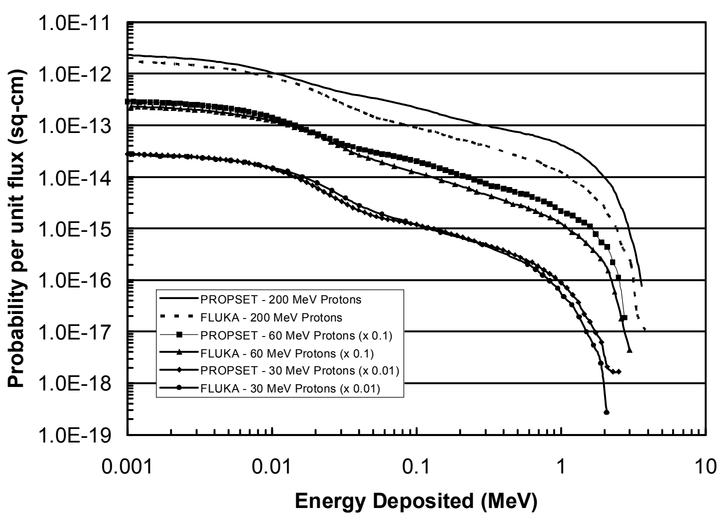

Figure 9: PROPSET and FLUKA (ref) calculated energy deposition probability distributions for energy deposited in a 1 x 1 x 1 cubic micron silicon cube by secondary particles produced when protons of 200, 60 and 30 MeV are incident normal to one surface. The cube is surrounded by 6

microns of silicon on the side the protons enter and by 50 microns of silicon on the other three sides. The 60 MeV (30 MeV) curves have been multiplied by 0.1 (0.01) respectively so that the curves could be plotted on the same graph.

Table 3. Measured and PROPSET calculated single event upset cross-sections caused by 200 MeV Protons for a number of parts compared to the upper bound cross-sections of Edmonds (ref). The cross-section calculated with PROPSET for a length to width of the sensitive volume of 10 to 1 divided by the cross-section for L to W of 1 to 1 and the thickness that, when used in a PROPSET calculation, results in a cross-section equal to the measured cross-section are also listed for each part.

Part #	Data Device Xsection (cm^2)	Edmonds Upper Bound Xsection (cm^2)	PROPSET Calculated Xsection (cm^2)	Edmonds Ratio UB/Data	PROPSET Ratio Calc/Data	PROPSET Ratio L to W (10 to 1)/(1 to 1)	PROPSET Fitted Thickness (microns)
1	3.14E-07		5.82E-08		0.19	0.98	
2	1.42E-07	9.6E-08	1.10E-07	0.70	0.78	0.98	
3	4.61E-07		3.69E-07		0.80	0.97	
4	9.00E-08		1.75E-07		1.94	0.88	3.00
5	8.70E-08	2.3E-07	2.71E-07	2.60	3.12	0.84	3.10
6	7.00E-07	1.9E-06	2.08E-06	2.70	1.40	0.99	3.10
7	1.47E-07	3.8E-07	4.64E-07	2.60	3.15	0.90	5.00
8	2.12E-08	5.8E-08	3.85E-08	2.70	1.81	0.45	0.30
9	3.94E-07	1.0E-06	1.14E-06	2.50	2.90	0.91	4.00
10	3.27E-07	8.9E-07	8.69E-07	2.70	2.66	0.87	3.30
11	4.19E-09	3.1E-08	1.68E-08	7.40	4.01	0.45	0.47
12	2.94E-07	1.2E-06	9.41E-07	4.10	3.20	0.94	5.10
13	4.59E-08	4.7E-08	8.98E-08	1.00	1.96	0.91	4.40
14	2.89E-08	5.0E-08	4.06E-08	1.70	1.41	0.69	1.60
15	8.50E-10	2.1E-09	3.77E-09	2.50	4.43	0.92	8.00
16	1.00E-06	2.0E-06	2.07E-06	2.00	2.07	1.04	7.30
17	2.98E-08	9.6E-08	1.17E-07	3.20	3.91	0.92	4.80
18	6.90E-07	2.9E-06	3.45E-06	4.20	5.00	0.96	9.50
19	1.46E-06	2.5E-06	2.72E-06	1.70	1.86	1.05	8.70
20	2.12E-08	8.2E-08	7.76E-08	3.90	3.66	0.46	0.52
21	1.76E-06	2.3E-06	2.48E-06	1.30	1.41	1.08	8.00
22	4.59E-10		2.06E-09		4.49	0.85	3.90
23	3.12E-08		3.08E-08		0.99	0.87	0.90
24	2.46E-09	1.6E-08	1.82E-08	6.50	7.41	0.84	2.70
25	8.68E-08		9.88E-08		1.14	1.07	2.25
26	2.98E-08		3.61E-08		1.21	1.06	2.35

CONCLUSION

PROPSET, a new Monte Carlo simulation code developed to predict proton induced single event upset cross-sections from measured heavy ion data using the position-dependent energy deposition threshold method suggested by Petersen et al. [5], has been described and results of calculations for the Xilinx

Virtex-II FPGA , SMJ44100 and a number of other parts compared to measured cross-sections. Good agreement was observed for the Xilinx Virtex-II FPGA , but PROPSET over predicts cross-sections due to 200 MeV incident protons for many parts. Sensitivity of PROPSET calculations to the shape and thickness of the sensitive volume, to the variation in Weibull parameters obtained by fitting heavy ion cross-section data and to model physics differences in Monte Carlo transport codes are examined and shown to make upset cross-section predictions by such codes uncertain by about an order of magnitude.

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