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Anomalies due to Single Event Upsets

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This paper reviews the simple idea of single event phenomena presented in the Air Force Geophysics Laboratory spacecraft anomalies handbook, and outlines how they can be extended to compare seemingly conflicting ground-test results.

Nomenclature

b = constant in a linear fit to the cross section
D = distribution of path lengths d through the sensitive volume
d = path length of a particle
d_{max} = longest distance through the sensitive volume
E = energy of the particle
f_z = flux as a function of energy for each ion species
L = linear energy transfer of the particle causing the upset
L_{max} = largest linear energy transfer for the particle environment
m = slope in a linear fit to the cross section
Q_{crit} = critical charge is the thickness of the sensitive region times L
Z = atomic number
θ = colatitude angle
σ = cross section
ϕ = longitude angle
Ω = solid angle

Introduction

SINGLE event events are aberrations in analog, digital, or even power circuits caused by the interaction of a single particle with the circuit. Single event upsets (SEUs) are now reasonably well understood. Handbooks and review articles are available which define terms and describe the processes. There is a rapidly growing literature in this area, and substantial parts of conferences now cover this phenomenon. Engineering estimates can be made for the rate of single event upsets for parts based on test results on the ground. However, continuing work is needed as parts become more complex, and details of the processing are improved or modified. Comparisons between different experiments sometimes reveal discrepancies between results using standard SEU models, but slightly more complex theory suggests that these discrepancies will be resolved by more detailed modeling. This paper will emphasize digital electronics, but the concepts apply to analog and power circuits as well. The introductory sections are largely a synopsis of the Air Force Geophysical Laboratory (AFGL) spacecraft anomalies handbook.[1] The last part uses these concepts to resolve an apparent contradiction between experimental results.

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Single particles interact with electronic circuits because they produce a conductive path through the circuit as they pass through the device. This conductive path is produced as the particle ionizes the atoms of the material it is passing through. This is the same mechanism that accounts for the shielding effectiveness of materials to charged particles. Single particles of high energy can be considered fully ionized as they penetrate solid materials. The particle loses energy by exciting or ionizing electrons from the atoms it passes, creating electron hole pairs along its path. The amount of energy lost to the particle as it travels through matter depends on the particle and the matter it is traversing.[2] The amount of energy lost to the particle per unit path length is referred to as its stopping power or its linear energy transfer (LET). A particles' LET is also a function of the energy of the particle. Figure 1 shows the stopping power or LET of some particles as a function of energy of the particle. In this case the energy of the particles is normalized to energy of the particle per nucleon. This allows all of the particles to be conveniently plotted on a single scale and emphasizes the systematics of the slowing down process. Notice that all of the particles have a characteristic peak in LET (called the Bragg peak) followed by a broad minimum and a very slowly rising curve at relativistic energies. The higher the Z of the incident particle, the higher the LET at the same energy per nucleon.

In many digital memory circuits charge is used to store digital information. Any external process which significantly changes that charge can change the digital information. For example, when a flip-flop circuit is used to represent a digital bit, putting the charge on the off side of the circuit can cause the flip-flop to change state. SEUs are produced in these integrated circuits when a single particle produces enough charge in a sensitive region to change the state of the circuit.

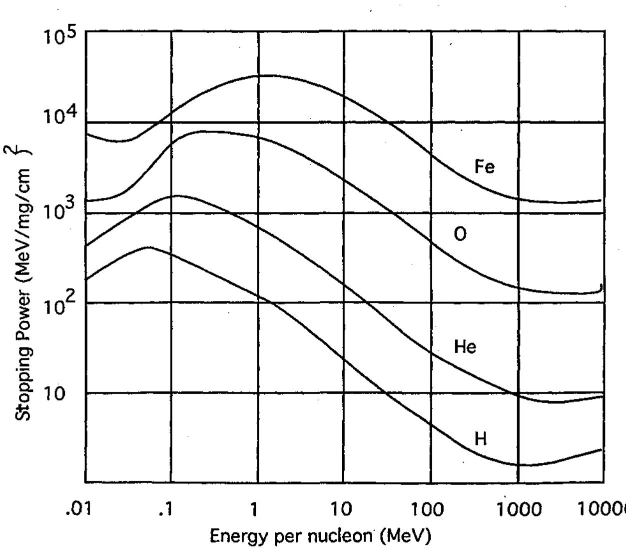

Fig. 1 Stopping power of ions in silicon.

SEUs are more common in memories simply because there are more memory locations susceptible to upset.

However, an SEU can occur in any type of digital logic or in analog and power circuits. This phenomena became a concern in the late 1970s, although it had been predicted earlier. As technology pushed toward faster and lower power devices a single bit was represented in the circuit by less and less charge. Thus, the charge produce by a single particle in a device that produced only a slight shift in the voltage level at a critical point in the circuit or a slight increase in noise in high power memory circuits would actually produce a change in the state in faster, lower power devices.

Basic Mechanism

Early experiments with digital SEU sensitive parts showed that to zeroth order the part would change state when exposed to particles with a linear energy transfer above a critical value. This lead to a simple approximation for calculating the single event upset rate. This model was supported by ground tests and soon became the standard model[3,4] for upset rate prediction. The simple argument goes as follows. When an ionizing particle passes though the depletion region of the off node in a flip-flop circuit, the electron hole pairs along the particles path are separated by the electric field across the depletion region. This results in a short pulse. If that pulse is large enough and lasts for a long enough period, the feedback of the circuit will cause the final state of the circuit to change. This is the same method which allows one to set the state of the circuit electronically. Figures 2 and 3 illustrate the essential elements of this simple model. In Fig. 2 the path of a cosmic ray through the device is illustrated by the straight lines. Depletion regions are formed at p-n boundaries depending on how voltages are applied to the circuit. The volume the particle must interact with is determined by the feature size. In the case illustrated in Fig. 2, the depletion region is the bottom p-n region. Thus, the cross section would be the area presented by that boundary to the incoming particle. In other situations, other areas in the circuit will be important. This area is shown in Fig. 3 as the cross section or probability of upset. The threshold in this simple model is determined by the amount of charge required to change the state of the circuit. This is determined by the path length through the depletion region. The charge inserted into the circuit at that point is determined by the energy deposited along the particles path. The energy deposited by the particle is the linear energy transfer (or stopping power) of the particle multiplied by the path length of the particle through the depletion region. The charge deposited in the depletion region is related to the energy by the average energy required in a given material to produce one electron

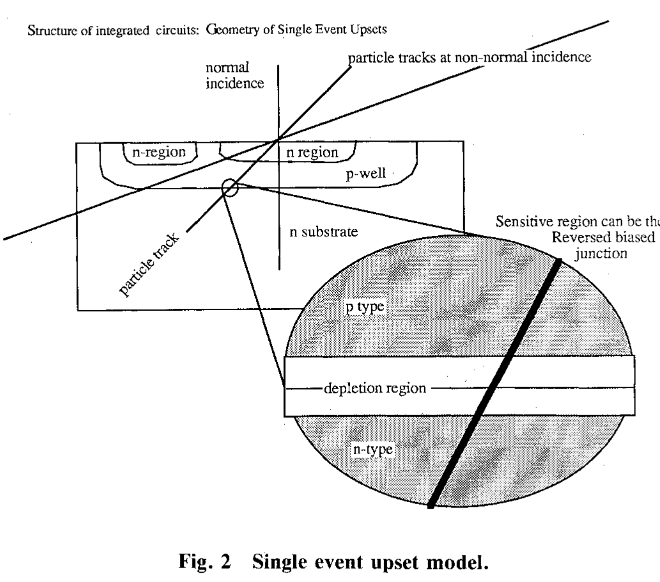

Fig. 2 Single event upset model.

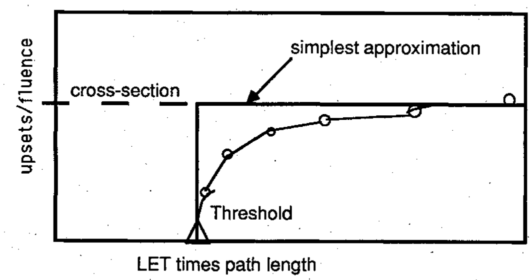

Fig. 3 Classical experiment cross-section and step function approximation.

hole pair. For silicon this is 3.6 eV. For GaAs it takes 4.8 eV to create one electron hole pair.

As a crude approximation, the amount of charge available to change the state of the device is one-half the total charge created. The factor of one-half allows for the fact that there is some recombination in the track, as the electrons and holes are transported across the depletion region. However, in analog circuits and for some power applications, the presence of a conducting path alone is responsible for the event. In some digital devices, the presence of a conducting path further influences the charge collection dynamics. This process, called funneling, is mentioned later.

In the 1980s typical silicon semiconductor devices used from 0.01 to 1 pC per bit in memory circuits. Feature sizes and depletion depths were on the order of 1μ. Referring to Fig. 1, for cosmic rays between 0.01 and 1000.0 MeV per nucleon (typical cosmic ray energies) any ion above hydrogen could cause an upset. It is very fortunate that hydrogen cannot directly cause SEUs in these parts since the number of hydrogens in cosmic rays is orders of magnitude higher than other ions. If hydrogen atoms could cause SEUs directly, the SEU rates for those parts could be expected to be 10^4–10^7 higher. Hydrogen can still cause SEUs by nuclear collisions. High Z atoms produced by the nuclear collision may have LETs and track lengths long enough to cause SEUs if the collision occurs close enough to a sensitive region. But since the probability for nuclear collisions is small, this process is much less likely than passing through the sensitive region without a collision.

For devices with a high charge per stored bit only very high Z incident atoms can cause an upset. These devices are relatively hard to SEUs because there are so few particles with LETs high enough to deposit sufficient charge in a sensitive region. However, parts which use a large charge per stored bit tend to be larger and more power hungry than those which can use a smaller charge to represent each bit.

Critical Charge or Threshold Linear Energy Transfer

The response of the integrated circuit (IC) depends as much on the dynamics of the electronics and the physics of the storage mechanism as it does on the charge deposited in the circuit. Memory devices can be broadly categorized as: 1) charge storage devices, 2) voltage storage devices, or 3) current steering devices. Devices which store charge for their memory, e.g., dynamic random access memories (RAMs) and charge coupled devices, determine their memory state by the presence or absence of charge. Voltage storage devices, e.g., static RAMs or CMOS RAMs, determine their memory state by the voltage which is present at certain nodes in a flip-flop circuit. Bipolar devices determine their memory state by steering currents such that certain transistors are in an "on" state. Common bipolar technologies for memory and processor applications include transistor-transistor logic (TTL) and integrated injection logic (I^2L). All of these devices have some susceptibility to single event upsets.[7,8] Nichols[9] ranks current technologies as shown in Table 1. Nichols also notes that P-Type Metal-Oxide Silicon (PMOS) is susceptible to SEUs. In all of these devices, whether understood in terms of voltage, charge, or current, the response of the circuit to a sudden input of charge or voltage shift due to the passage of an ionizing

Table 1 Susceptibility of technologies

CMOS/SOS (least susceptible)
CMOS
Standard bipolar
Low power Schottky bipolar
NMOS DRAMs (most susceptible)

particle can lead to a change in state of a digital circuit or erratic behavior in analog or power devices. Depositing charge at a certain point in the circuit is equivalent to changing the voltage at the point.

Consider a memory device which depends on a flip-flop circuit. The SEU is caused by the charge collected in a typical response time of the circuit. From a circuit point of view the current deposited by the heavy ion is injected at a node in the flip-flop circuit. The charge deposited in the IC is not instantly available to the circuit. Some is collected very quickly because the electric field in the depletion region collects it quickly. Other charge ends up at the same point in the circuit, but takes longer, either because it is a diffusion process which is responsible for separating and collecting the charge or the charge must travel a longer distance through the silicon. The charge collection at a node is illustrated in Fig. 4. The prompt charge is that which is collected in a typical response time for the circuit.

Without an electric field or differences in electron and hole mobility to separate the charge along an ion's track, there would be no net charge at a circuit node because the separated charges would eventually recombine. However, electric fields do exist for short periods of time within the silicon, and there are differences in mobility.

The existence of electric fields due to the passage of the ionizing particle has been proposed as a mechanism for the fast collection of charge outside the depletion region. This is called funneling. Funneling refers to the extension of the electric field which is usually confined to the depletion layer into the silicon beyond the depletion region. This is illustrated in Fig. 5. When this happens, the electron hole pairs which normally recombine or very slowly diffuse into the depletion region are rapidly collected by the temporary electric field and add to the total prompt charge collected after the ion passes through the chip. The charge collected when a funnel plays a role may be several times that expected from that collected along the path in the depletion region alone. The pulse still rises and falls in fractions of a nanosecond as it did when no funnel formed. Recent work has shown additional complications. For very heavy ionizing particles leaving a dense track recombination becomes important, decreasing the collected charge. For some structures that have very high electric fields, charge multiplication takes place, increasing the collected charge.

For devices with slow response times, the charge collected by diffusion can also be important.

The depletion region and funneled charges are separated and collected very quickly, on the order of a fraction of a nanosecond. The delayed diffusion component takes from one to hundreds of nanoseconds to finally be collected. The total cosmic ray pulse injected at the node of the circuit then is a sharply rising pulse with a rapid decay in a nanosecond or less, followed by a long, slow, small current representing the collection of charge which is diffusing from the ion track to the node as represented in Fig. 4. As long as the pulse width is considerably less than the circuit response time, the critical charge is independent of the shape of the pulse. For example, Pickel[7,8] frequently uses a trapezoidal pulse with a rise time of 0.01 ns and a full width at half maximum of 0.09 ns.

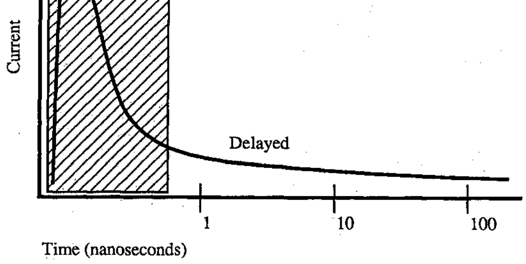

Fig. 4 Ion current pulse.

Cross Section for an Upset

The cross section for causing an upset is determined by the geometry of the sensitive region which we have identified in digital integrated circuits as the depletion region. The feature size, i.e., the typical dimension of regions on the chip, is important in determining the performance of the chip. The

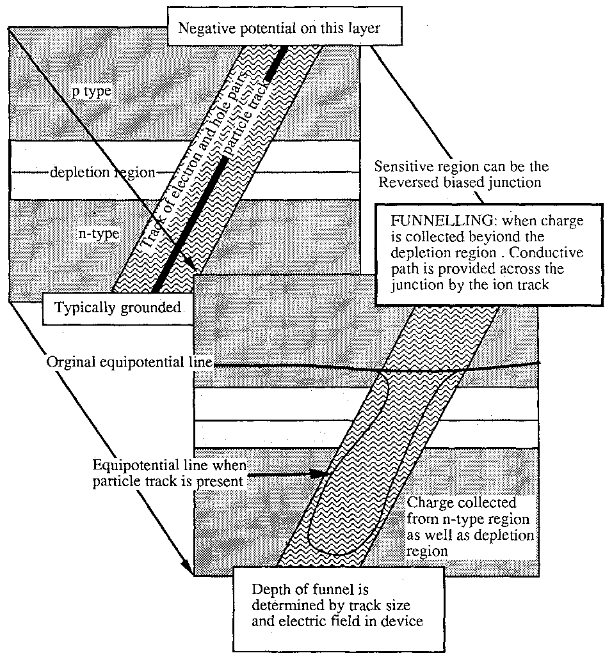

Fig. 5 Charged track funnel formation.

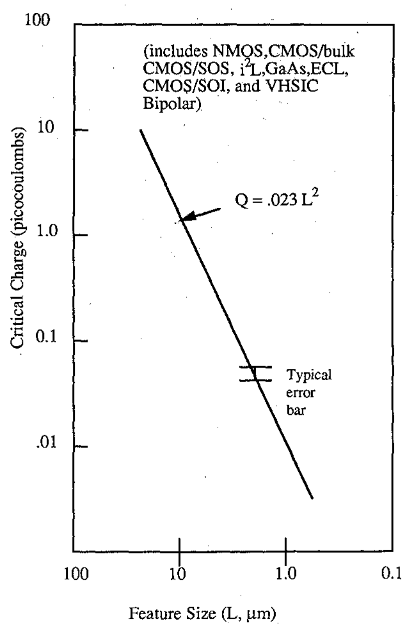

Fig. 6 Sensitivity vs feature size.

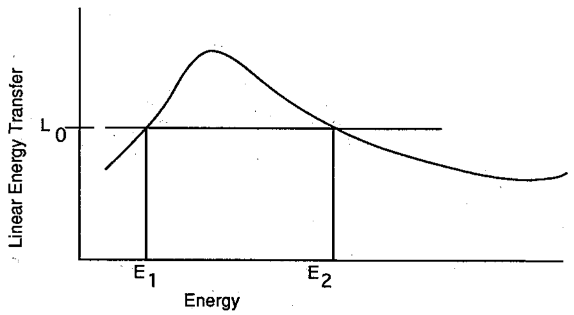

Fig. 7 LET distribution.

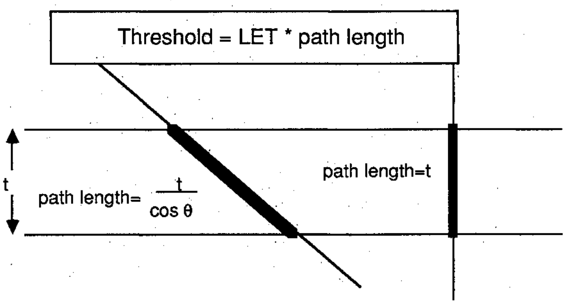

Fig. 8 Cosine law.

smaller the feature size is, the larger the memory on a single chip, the faster the processing speed, and the smaller the power required to maintain the memory. Competition among IC manufacturers places a premium on making the feature size as small as possible. Intuitively one would also guess smaller feature sizes result in smaller thresholds for SEUs. The charge stored on a node behaves like the capacitance of the node, i.e., $\approx A/d$ where A is the area of the device. For constant d, the depth of the depletion region, the critical charge is proportional to the feature size squared.

Figure 6 shows the measured critical charge plotted as a function of a feature size for a number of different technologies. The critical charge essentially follows the simple scaling rule $Q \sim 1/L^2$ over a wide range of device technologies and feature sizes L. This coupled with the advantages of low power, increased memory, and increased speed brought on by smaller feature sizes means that devices are likely to become more sensitive to SEUs as they "advance."

Calculation of Single Event Upset Rate

The upset rate is calculated by integrating the cross section, the path length distribution through the charge collecting region, the distribution of ions as a function of LET and spatial parameters, and the critical charge of the device. A general formulation of the problem is

$$\text{SEU rate} = \sum_{z=1}^{z=92} \int_0^{2p} d\phi \int_0^{p} d\theta \int_{E_1}^{E_2} dE f_z(E, \theta, \phi)\sigma(E, \theta, \phi) \quad (1)$$

Here the summation is over all ion species, and the integration is over all angles and over all energies in the interval (E_1, E_2) where E_1 and E_2 are defined later. As previously discussed, the cross section is a function of LET rather than energy, and so it can be removed from the energy integral and the summation over ion species. This means that the integral representation of the SEU rate can be simplified to

$$\text{SEU rate} = \int_0^{2\pi} d\phi \int_0^{\pi} d\theta\, \sigma(\text{LET}, \theta, \phi) \sum_{z=1}^{z=92} \int_{E_1}^{E_2} dE f_z(E, \theta, \phi) \quad (2)$$

Now the limits on the energy integral are the range of energies for each ion over which the LET is equal to or greater than the LET of concern (let). With this simplification the SEU rate integration can be broken up into independent parts, representing the external environment and the device characteristics. Although some work[11] indicates that this full separation is not accurate, there are many cases when this is true.

The second part of the integral focuses on the environment. The energy range for each ion species is that portion of the Bragg peak (see Fig. 1) such that the LET is greater than the given LET threshold. This is illustrated in Fig. 7. $E1$ and $E2$ are the energies between which the LET is greater than the LET threshold under consideration.

The separation of the SEU rate into a device part and an environment part allows a derivation of the final rate as a simple product of the Heinrich flux defined subsequently and the cross section.

$$\text{SEU rate} = \int_0^{2\pi} d\phi \int_0^{\pi} d\theta\, \sigma(L, \theta, \phi)\ \text{flux (LET} > L0) \quad (3)$$

The environmental part of the SEU rate

$$\text{flux (LET} > L0) = \sum_{z=1}^{z=92} \int_{E_1}^{E2} dE f_z(E, \theta, \phi) \quad (4)$$

is sometimes referred to as a Heinrich curve after the researcher who used it in investigating the effects of cosmic rays on genetics.[12]

The planar structure of an IC suggests that the depletion region over which the charge is collected is a box. Thus, as the angle of the incoming flux is varied, the path length through the sensitive region is lengthened by a factor of one over the cosine of the angle of the path to the surface, as shown in Fig. 8. The result is the same as if you had normal incident particles with an effective LET given by

$$L_{th}/\cos\theta = L_{ef} \quad (5)$$

Most experimenters take advantage of this effect, by assuming a rectangular sensitive volume and using the $1/(\cos\theta)$ dependence to determine the threshold. When a normally incident particle does not cause an upset, the chip is rotated in the beam. If upsets occur at the angle q then the threshold is LET/cos θ, where LET is taken as the particle as it crosses the sensitive region.

In this view, single particle effects including SEUs and latchups are highly dependent on the path lengths of incident

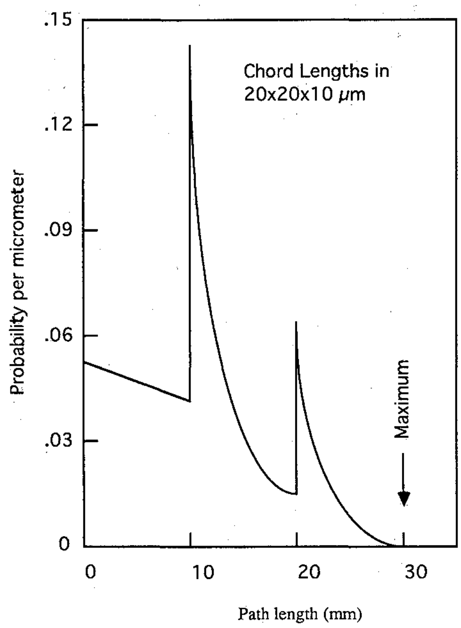

Fig. 9 Path length distribution function.[12]

particles within sensitive device regions. A sensitive region that is cubical has path lengths that vary from zero to the square root of three times the thickness of the sensitive volume, whereas parallelepipeds can have a more complex distribution of possible path lengths. Shapiro et al.[13] showed the equivalence of equations with the integral path length distribution used by Pickel and Blandford,[14] calculated some examples for SEUs, and discussed some of the approximations being used. Bendel[15] greatly simplified these equations and investigated the characteristics of the distribution. Various forms of the distribution equations along with other techniques are included in the current SEU models being used. Figure 9 shows a typical chord length distribution. In this case the spikes characteristic of a path through the volume in the direction of one of the sides of the box show up at 10 and 20 (the box dimensions). The actual thickness of the sensitive region of the device can be determined experimentally by varying the ion species and energy of the incident particles and noting the SEU rate. Often times the depletion depth is taken as the thickness of the sensitive volume, when this is known, or it can be determined from doping profiles.

In the case where we can simplify to a geometrical model, the upset rate calculation can be simplified using the ideas of effective threshold, path length, and path length distribution. This is shown in the following equations:

$$\text{rate} \rightarrow \int \Phi(L)\sigma(L_{th})\, d\Omega$$

$$L = L_{th}/\cos\theta$$

$$\sigma = \sigma_0 \cos\theta$$

$$\sigma_0 = mL + b$$

$$d\Omega = -d\varphi\, d\cos\theta \qquad (6)$$

A step function cross section and LET threshold then describe the part sensitivity. Using the preceding equations and expressing $d\cos\theta$ in terms of dL

$$d\cos\theta = \frac{L_{th}}{L^2}\, dL \qquad (7)$$

The rate equation takes the following form:

$$\text{rate} \rightarrow \int_{L_1}^{L_2} \Phi(L)\sigma(L_{th})\, d\Omega = \frac{m\Phi(L)}{L} + \frac{b\Phi(L)}{2L^2} \qquad (8)$$

where the integral is carried out for each interval and evaluated at the end points of the interval in the usual manner. For a constant cross section, $m = 0$, and the rate is the cross section b times the Heinrich flux.

A simple modification to this model to account for particles which "hit the edge of the sensitive region" is to add a cross section which is proportional to the thickness times a typical dimension of the measured cross section, $\sqrt{\sigma}$ for particles in a solid angle proportional to $t\sqrt{\sigma}$. This results is an edge hitting contribution that is proportional to $(t^2\Phi)$ $t{*}t{*}$ the Heinrich flux. To account for regions where the thickness is longer than a typical dimension on the surface of the sensitive region, the Heinrich flux is scaled by taking the Heinrich flux at the threshold LET times $t\sqrt{\sigma}$.

Using the distribution of paths lengths, the rate is

$$\text{rate} \rightarrow \sigma \int \Phi(L) D[d(L)]\, d\Omega \qquad (9)$$

The "cross section" is now just a number in front of the integral. In practice we make the same change of variable and integrate over L rather than angle. For example, Adams uses the following in his popular SEU code Creme,

Table 2 Conflicting results

Ion	Average energy, MeV	LET MeV/mg/cm^2	Cross section, cm^2
O	24.1	1.0	1.8(−4)
O	7.4	2.7	2.8(−4)
O	6.3	3.1	6.3(−3)
O	2.2	5.2	4.0(−3)
Ar	11.6	8.7	3.2(−2)
Ar	2.2	17	1.3(−2)
Xe	23.0	36.0	5.0(−2)
Kr	3.6	37	4.0(−2)

Table 3 Charge collection efficiency trend

Ion	Average energy	LET × CCE	Cross section	CCE
O	2.2	3	4.0(−3)	decrease
O	24.1	1.5	1.8(−4)	increase
O	7.4	3	2.8(−4)	
O	6.3	3	6.3(−3)	
Ar	2.2	9	1.3(−2)	decrease
Ar	11.6	14	3.2(−2)	increase
Kr	3.6	18	4.0(−2)	decrease
Xe	23.0	18	5.0(−2)	decrease

$$\text{rate} = 22.5\pi\sigma Q_{\text{crit}} \int_{\frac{22.5Q_{\text{crit}}}{d_{\max}}}^{L_{\max}} D[d(L)]\text{flux}(\text{let} > L_0)\frac{dL}{L^2} \qquad (10)$$

where the flux is the Heinrich flux calculated in the code; the critical charge is based on the threshold LET and the thickness of the sensitive region; 22.5 is a number that keeps things in the proper units assuming that it takes 3.6 eV to create an electron hole pair in silicon. In the case of a sensitive volume that is $\sqrt{\sigma}$ on a side and t thick, this is

$$d_{\max} = \sqrt{2\sigma + t^2} \qquad (11)$$

Conflicting Data

For all single particle effects, the effective sensitive region is determined by all of the effects—funneling, straggling, diffusion, etc.—that influence the charge collection in the device. Consider the data shown in Table 2. At high LETs the cross section measurements differ by 20%. This may be well within the experimental uncertainties. However, at lower LETs, in particular the oxygen 7.4 and 6.3 MeV/amu results, a small change in LET results in an order of magnitude change in cross section. Although this is in the steep part of the cross section curve the points do not present a monotonic picture of the cross section in that LET range. Researchers at the Naval Research Laboratory have shown[16] that the charge collection efficiency of a device depends, among other things, on the energy of the particle. Higher energy particles produce a less dense track. A dense track will allow more recombination of electron hole pairs than a less dense track. Adding charge collection efficiency will tend to move low energy points to smaller effective LET and higher energy points to higher effective LET. Measured variations were as high as 50%. If we assume that the charge collection efficiency makes a 50% change depending on whether or not the energy per atomic mass unit is above or below the Bragg peak then the results tend to come into alignment as shown in Table 3. The alignment is far from perfect. One does not know how measurements near the peak (like the 6.3 and 7.4 MeV oxygen measurements) are going to be affected.. But still the trend of the correction is in a reasonable direction. More detailed calculations are needed.

Conclusion

We would argue that the simple geometric and physical model presented for SEUs with its ability to include more complicated effects as they are quantified and understood makes single effect events in all types of electronics reasonably well understood. Engineering estimates can be made for the rate of single event upsets for parts based on test results on the ground. Continuing work is needed for more complex parts as well as more detailed measurements.

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