Summary

This paper examines the problem of soft errors in semiconductor devices caused by the protons in the radiation belts. The errors can be produced by a variety of nuclear reactions in silicon. A previous paper presented a calculation of the likelihood of some of these reactions. This information can be combined with knowledge of the proton environment in order to estimate the upset rate for various devices in spacecraft. This paper discusses the proton environment, the effect of spacecraft shielding, the various proton induced reactions in silicon, the calculation of soft error sensitivity, and the soft error rate in a representative satellite.

The Environment

Present spacecraft operate in two distinct regions of space: a lower region between 100 and 600 nmi (185-1111 km) and an upper region above 10,000 nmi. However, future spacecraft may have to operate between 600 and 6000 nmi, in the intense proton belts. Figure 1 indicates the number of high energy protons in these regions. These protons can pass well into a satellite. Figure 2 shows the trapped proton spectrum for a 600 nmi (1111 km) orbit. The shape of the spectrum changes as the protons lose energy passing into the spacecraft. The spectrum in the interior can be obtained by following this energy loss through concentric shells of increasing thickness to produce the spectra shown by the dashed curves in Figure 2.

Figure 2 The omnidirectional trapped proton flux for a 600 nmi orbit. The dashed curve shows the flux after passing through various thicknesses of concentric shells. The inner solid curve shows the resulting spectrum after the incident flux passes through the shield distribution of Figure 3.

The actual shielding surrounding any satellite component is not uniform. Figure 3 shows the shield mass distribution surrounding a typical component in a light (< 500 lbs) spacecraft as calculated by Langworthy using a sector analysis code. This mass distribution can be used to assign a relative weight to the contribution of each concentric mass shell and then obtain the resultant spectrum at the typical component. This is shown by the inner solid curve in Figure 2. We see that an increase of the minimum thickness will have only a small effect on the spectrum. In general, it is useless to attempt to reduce proton exposure by adding shielding. The resultant spectrum in Figure 2 peaks at approximately 40 MeV and has a tail to several hundred MeV. We then want to understand the effects of the various proton induced reactions between 10 and 200 MeV.

Figures 1 and 2 show the number of protons averaged over long time periods. Actually, in low earth orbits, the protons arrive during only a fraction of the orbit. Figure 4 shows the integral flux as a function of time for a worst case orbit at

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SHIELD MASS DISTRIBUTION

THICKNESS (INCHES–Al)

FRACTION OF SOLID ANGLE

THICKNESS (G/cm²)

Figure 3 The shield mass distribution surrounding a typical component in a light spacecraft.

1111 km that is, one going through the peak of the South Atlantic Anomaly (SAA).(1) The strongly pulsed nature of the proton flux that the satellite experiences could temporarily degrade the performance of devices that are sensitive to single particles. It also suggests that in some applications it might be sufficient to read and correct the memory once per revolution, and that there would be very few errors introduced until the next pass through the SAA.

Figure 4 The trapped proton flux as a function of time for an orbit passing through the South Atlantic Anomaly.

Proton Induced Reactions

Not enough attention has been paid to upsets produced by protons whereas soft errors produced by heavy ions have been studied extensively. These ions produce a very dense ionization track and therefore can directly upset a memory cell. Protons, on the other hand, are lightly ionizing and not apt to produce upsets directly in present day memories. Figure 5 shows the ionization produced by protons and proton induced events. In a 10 μm slab of silicon, only 3.6 out of every 10³ incident 40 MeV protons will produce a nuclear reaction. (The total reaction cross section is 725 mb) Nevertheless, the fluxes indicated in Figures 1, 2 and 4 are high enough so that these secondary events are important. We now want to assess the relative contribution of the various classes of proton initiated reactions.

Figure 5 An overview of the reaction processes that lead to ionization by protons in silicon.

Let us first examine elastic scattering. In principle this could be very important as the maximum possible energy of the recoiling heavy nucleus increases linearly with the energy of the incident proton. It we assume that it takes 3.6 eV to create an electron–hole pair, then an energy deposition of 3.6 MeV will produce 10⁵ electrons. We say that a device has a sensitivity of 10⁵ electrons (critical charge) if an event depositing this energy in the sensitive volume will produce a memory upset. Any energy deposit above the cutoff energy of 3.6 MeV will cause an upset. Figure 6 shows the cross section for elastic scattering events(3–9) that deposit more than a given energy for a number of incident proton energies. We obtained the curves by transforming the angular data from dΦ/dΩ to dΦ/dEₐ and then integrating the curves for Eₐ > Eₐ. Not only are the cross sections in general small, but above 40 MeV they also decrease rapidly with increasing energy.

Early investigators identified alpha particles from natural radioactivity in the device packaging.
Figure 6 The cross section of elastic scattering events that produces a recoil ion with energy greater than $E_c$ for various incident proton energies in MeV.

as the source of many soft errors in memory devices. This led to the suggestion that the alpha particles produced in nuclear reactions should also be important. In Figure 7 we examine a typical reaction in silicon. Here we have a compound nucleus being formed by the initial proton and silicon atom, followed by the evaporation of a proton, followed by the evaporation of an alpha particle. During each of the 3 steps the nucleus recoils and its velocity adds vectorially to its previous velocity. In this example we could have approximately 10 MeV deposited in the maximum path length available (30 μm) in the assumed sensitive volume of 20 μm x 20 μm x 10 μm. Other combinations of particle energy could increase or decrease the total slightly. As the incident proton energy increases, so does the likelihood of a preequilibrium situation in which the proton only briefly interacts with the nucleus, imparting only enough energy so that a single alpha particle or proton evaporates. Therefore the maximum recoil energy will remain near the value it had for 30-40 MeV protons.

The reactions that can deposit the most charge in the silicon are the spallation (fission) reactions in which the compound nucleus breaks up into two heavy fragments. In this case most of the energy is carried by two heavy particles, both of which can stop in the sensitivity volume. The approximate maximum energy that can be deposited in a 30 μm path by the various processes is summarized in Table 1. The last column shows the number of

<table>
<thead>
<tr>
<th>Reaction Class</th>
<th>Max. Energy Deposited</th>
<th>Electrons Released</th>
</tr>
</thead>
<tbody>
<tr>
<td>1) Direct ionization by protons</td>
<td>0.08 MeV</td>
<td>0.02x10^6 electrons</td>
</tr>
<tr>
<td>2) Reactions not producing heavy particles</td>
<td>2.3 MeV</td>
<td>0.6x10^6 electrons</td>
</tr>
<tr>
<td>3) Elastic scattering recoils</td>
<td>5.3 MeV</td>
<td>1.5x10^6 electrons</td>
</tr>
<tr>
<td>4) Reactions producing alpha particles</td>
<td>10 MeV</td>
<td>2.8x10^6 electrons</td>
</tr>
<tr>
<td>5) Spallation reactions $^{16}$O+$^{12}$C</td>
<td>22 MeV</td>
<td>6 x 10^6 electrons</td>
</tr>
</tbody>
</table>
electrons freed. The electron-hole recombination that takes place in very highly ionized regions of silicon is not considered. This effect would be more important as the ionizing particle gets heavier, especially for recoiling silicon and magnesium nuclei. The maximum energy deposited can be calculated at various energies as desired. It depends upon the maximum path length and upon the energy available in the reaction. There is nearly a constant maximum energy for each of the various processes above 60 MeV proton energy.

In order to establish the upset rate due to a continuous energy spectrum, one needs the reaction cross section as a function of energy. This is shown in Figure 8, along with contours of elastic scattering cross sections for various recoil energies obtained in the same analysis that led to Figure 6. The effect of elastic scattering peaks at 40 MeV. Spallation and alpha producing reactions have nearly constant cross sections above 60 MeV.

**CROSS SECTIONS FOR p + Si REACTION PROCESSES**

![Diagram](image)

Figure 8 The energy variation of various processes that can produce ionization, and therefore upsets, in silicon.

**Soft Error Calculations**

The information gathered in the previous section is valuable in two aspects. 1) It can be used to identify the most important nuclear contributions to soft error effects. This knowledge will point to future research and to upset problems that will arise due to nuclear reactions as device sizes are scaled down. 2) It can be used to systematize measured cross sections so that they are useful for estimating upset rates in proton environments.

The number of nuclear events that can deposit various amounts of charge in an assumed collection volume is calculated. These results can be plotted as upset cross section versus device sensitivity. A curve at one energy showing the total upset cross section as a function of device sensitivity then gives a characteristic charge corresponding to the measured value of upset cross sections. A family of curves of upset cross sections at various energies as a function of device sensitivity can be combined with the proton environment to give a curve showing upset rate as a function of characteristic charge. A measurement of upset cross section leads to a unique characteristic charge which in turn leads to a unique upset rate in a satellite environment.

Figure 9 shows the calculated upset cross sections at 40 MeV as a function of device sensitivity for an assumed sensitive volume of 20 μm x 20 μm x 10 μm. The effects of ionization by primary protons can be calculated using the methods described in Pickel and Bradford. Upsets due to direct ionization by 40 MeV protons will only occur at very low critical charges but lower energy protons can give contributions up to 4 x 10^5 electrons. The upset cross section due to elastic scattering can be calculated nearly exactly, as the energy deposit is by the short range heavy particle. All scattering events that take place in the sensitive volume, depositing more than the critical charge, will cause upsets. We can parametrize the curves due to the nuclear reactions by the maximum energy deposited, giving maximum number of electrons produced; and the maximum reaction cross section, giving the maximum possible upset cross section. Both ends of the curve are established, but not the middle. The detailed shape of the midsection depends on ionization by several particles of random energy going in random directions and has not been calculated.

**Figure 9** The upset cross section (right scale) as a function of device sensitivity for a sample device exposed to 40 MeV protons. If we assume a flux at 10^6 p/cm² day on a memory of 64 megabits, we obtain the upset rates according to the left hand scale.

It is clear from this figure and from Table I that a major contribution to soft upsets in satellite environments comes from the nuclear reactions that emit heavy particles. This is an entirely different situation from the case of upsets.
produced by alpha particles emitted by the device packaging. At the same time, any device upset by alpha particles will certainly be upset when exposed to the trapped proton environment.

Figure 9 is an example of a family of curves that have been calculated for various proton energies for the specific geometry shown. These curves are unique for a given geometry and proton energy, so that there is a one to one relationship between the upset cross section and the device sensitivity. The curve for other proton energies are essentially the same as the curve of Figure 9, except that there is a direct ionization contribution in the case of very low energy protons that stop or nearly stop in the device; and the spallation reactions are slightly more important in the case of the high energy protons. Figure 10 repeats the curve of total upset cross section versus device sensitivity of Figure 9 and shows some representative values of measured upset cross sections for actual devices, indicated by the arrows on the right scale. We use this curve to determine a characteristic charge for a given device. This characteristic charge will correspond to critical charge only for devices with the same geometry used here.

Figure 10 Measured upset cross sections for protons compared with the sensitivity curve shown in Figure 9. This gives a measure of the device sensitivity.

The set of curves of upset cross section at various energies, of which Figure 9 is an example, can be combined with the proton spectrum of Figure 2 to obtain a sensitivity curve for a particular orbit and spacecraft. Figure 11 shows the resultant curve for a 1111 km orbit.

Since the shape of the upset cross section curves are relatively independent of the exact geometry of a device, a curve such as that in Figures 9 and 10 can be used together with the curve of Figure 11 to obtain an upset rate for similar devices. There will be little error introduced by obtaining a characteristic charge corresponding to a measured upset cross section in Figure 10; and then using this characteristic charge in Figure 11 to determine an upset rate. The relative ordering of measured upset cross sections and of upset rates in the satellite environment will remain the same.

As an example of error rate calculation, consider the Intel 21147H which has a measured upset cross section of approximately $2 \times 10^{-11}$ upset/proton bit. This corresponds to a characteristic charge of $7 \times 10^6$ electrons. (Figure 10) We obtain a soft error rate of $10^{-9}$by using this charge in Figure 11. This rate directly scales to other memory sizes; and, using Figure 1, to other circular orbits.

We have emphasized the large number of errors that may occur. In some applications these might not be important if the errors act like slight additional noise in an already noisy set of raw data. However if a single error occurs in the results of data analysis, in a program controlling a thruster, or in a register containing program step or time, it might be very significant. If the ten thousand errors of the example are in a memory of $1.64 \times 10^{10}$ 39 bit words (32 bits + 7 error correcting bits), there would be 30 words with two errors. Standard error correction techniques would detect but not correct these errors. In most applications this would be sufficient. A careful analysis of soft error probability and importance should be made for any memory to be carried in the radiation belts. In particular the error rate of any device containing memory cells should be measured using protons above 40 MeV. The reactions involving heavy particles are important in the satellite environment and are not considered when using alpha particles or 14 MeV neutrons.

![Figure 11: Upset rates in a sample satellite memory for the spectrum at the device as a function of device sensitivity.](image-url)
Conclusion

This paper has examined the high energy proton environment that semiconductor devices would see inside a representative satellite. It then considered the magnitude and energy dependence of proton elastic scattering and proton-induced nuclear reactions in silicon. These data were used to obtain a sample device sensitivity for 40 MeV protons. Consideration of a set of such curves for various energies led to a sensitivity curve for the calculated proton environment. One can then use measured upset cross sections in the vicinity of 40 MeV to calculate upset rates in the satellite environment. These calculations were performed for a 600 nmi orbit, but are easily scaled to other orbits. The results lead to the following conclusions:

1. The soft error problem needs to be considered in the design of any satellite that carries semiconductor memory in the radiation belts.
2. In low earth orbit, the soft errors will occur principally as the satellite passes through the South Atlantic Anomaly.
3. The integrated soft error rate increases as the satellite's orbit is moved into the heart of the radiation belt.
4. The soft error problem becomes more important as the memory uses higher density memory chips.
5. A very important component of the soft error effect in the radiation belt environment is due to the dense ionization by heavy recoil nuclei and spallation products.
6. Measurements of upset susceptibility due to alpha particles from alpha sources is not adequate. One needs to measure upset cross sections in high energy proton beams of 40 or more MeV.

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References

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