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The Effects of High Energy Particles on Planetary Missions

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Introduction

NASA is currently planning and building space systems for use in the 90's. An important part of the system design is understanding the environment and its effects on the system. These effects include spacecraft charging, internal charging, and degradation due to radiation. Most of these effects are reasonably well understood and have been studied for a considerable period of time. Voyager, for instance, had an extensive and apparently successful radiation control program which included prediction of the environment, prediction of the effect of the environment on systems and parts, and appropiate engineering response to the assessed degradation of the spacecraft due to the radiation environment.

However, the extensive use of modern, low power, high speed electronics has brought new concerns to the engineering community. Modern electronics have become so fast and so small that a single particle can influence their behavior -- a single particle can cause the electronics to malfunction in contrast to the cumulative effect of a multitude of particles required to cause earlier electronics to malfunction. Over the past five or so years, single event upsets -- situations where a heavy ion causes a flip-flop circuit in the chip to change state, have received a great deal of attention. Several conferences now devote a considerable fraction of their attention to this phenomenon. The IEEE Nuclear and Space Radiation Effects conference in July and the Single Event Effects Annual Symposium in April are two conferences which devote a considerable amount or all of their time to single event phenomena (SEP).

A prime consideration in the calling of this conference on the environment at this time, in addition to the fundamental importance of the environment in planning and designing space missions, is a new development in electronic part sensitivity. In addition to single event upsets, which are primarily soft errors, it is possible for modern electronics to latchup. A latchup many times results in a total failure of the electronic part, and consequently a possible loss of the mission. As will be shown later, this concentrates attention on the behavior of heavy ions in solar flares, and those trapped in the earth's radiation belts.

In this paper, we will review the background and motivation for detailed study of the variability and uncertainty of the particle environment from a space systems planning perspective. The engineering concern raised by each environment will be emphasized rather than the underlying physics of the magnetosphere or the sun. The rest of the papers in this conference will concentrate on the physics and predictions of the environment.

Missions now being planned span the short term range of one to three years to periods over ten years. Thus the engineering interest is beginning to stretch over periods of several solar cycles. Coincidentally, detailed measurements of the environment are now becoming available over that period of time.

Both short term and long term environmental predictions are needed for proper mission planning. Short term predictions, perhaps based on solar indices, real time observations, or short term systematics, are very useful in near term planning --

launches, EVAs (extravehicular activities), coordinated observations, and experiments which require the magnetosphere to be in a certain state.

Long term predictions of both average and extreme conditions are essential to mission design. Engineering considerations are many times driven by the worst case environment. Knowledge of the average conditions and their variability allows trade-off studies to be made, implementation of designs which degrade gracefully under multi-stress environments, the exercise of mission options based on near real time updates to environmental predictions, and prevents rejection of environmental considerations as nescient. Even the bounding of conditions over a mission duration is of considerable importance to mission planning, although that may not be very satisfying to the modeler who is attempting to predict real time variations, or to understand the details of magnetospheric activity.

Current Planning

A specific mission is concerned with the time and spatial variations of the environment along its trajectory. Current planetary missions with destinations as far as 1000 AU and as near as the sun are being planned. In the table below, some of the unmanned missions under consideration are listed, along with possible radiation induced engineering concerns. Many more manned and unmanned missions are possible and perhaps more likely. The point is, all missions need to consider the radiation environment.

Table: Some Current Missions

Project	Purpose	Possible Radiation Concern
Magellan	Radar mapping of Venus	Latchup of digital radar unit and single event upsets in memory especially during large solar flares
Starprobe	Investigation of the sun	Intense solar radiation -- heat shield; solar flares producing radiation damage, single event upsets and latchup.
Mariner Mark II	General purpose research craft planetary exploration	Wide range of possible environments. Concern ranges from single particle phenomena to radiation damage
TAU (Thousand AU)	Explore the outer reaches of the solar system	Extremely long mission and trajectory make tolerance to radiation induced problems a strong concern. Robust system design is called for.

Radiation Effects on Electronics

We review briefly some of the major radiation concerns that have historically been considered in planetary programs. This is followed by a short review of latchups.

Historically, the discovery of the Van Allen belts inaugurated space exploration and simultaneously initiated radiation damage as a concern for future space exploration. Since that time radiation damage to man and electronics has played a role in the planning and implementation of all space programs. The principal concern, until recently, has been the damage that a large number of particles inflict on solid state parts. This concern is usually referred to as a total dose problem.

Total Dose

There are two categories of total dose concern for electronics -- displacement damage and ionization. In one case the charged particle actually displaces an atom in the solid state structure and thereby modifies the mobilities etc. of the device.

Ionization along the track of a particle deposits charge and energy in the device which ultimately influence its operation. For example, thin insulating regions in the device collect charge at the interface between the insulating area and a semiconducting region, and thereby influence the current flow in the semiconductor. Programs have specified total dose tolerance for a number of years. For example, in the Galileo program the electronics radiation requirements are as follows:

Environment	Displacement	Ionization
Protons	4E10p/cm-sq 20MeV equivalent	electrons dominate (except surfaces)
electrons	Ions dominate	150 krads(Si)
Neutrons	5E10 n/cm-sq 1 MeV equivalent	negligible
Heavy ions	protons dominate	electrons dominate
Gamma	Negligible effect	electrons dominate

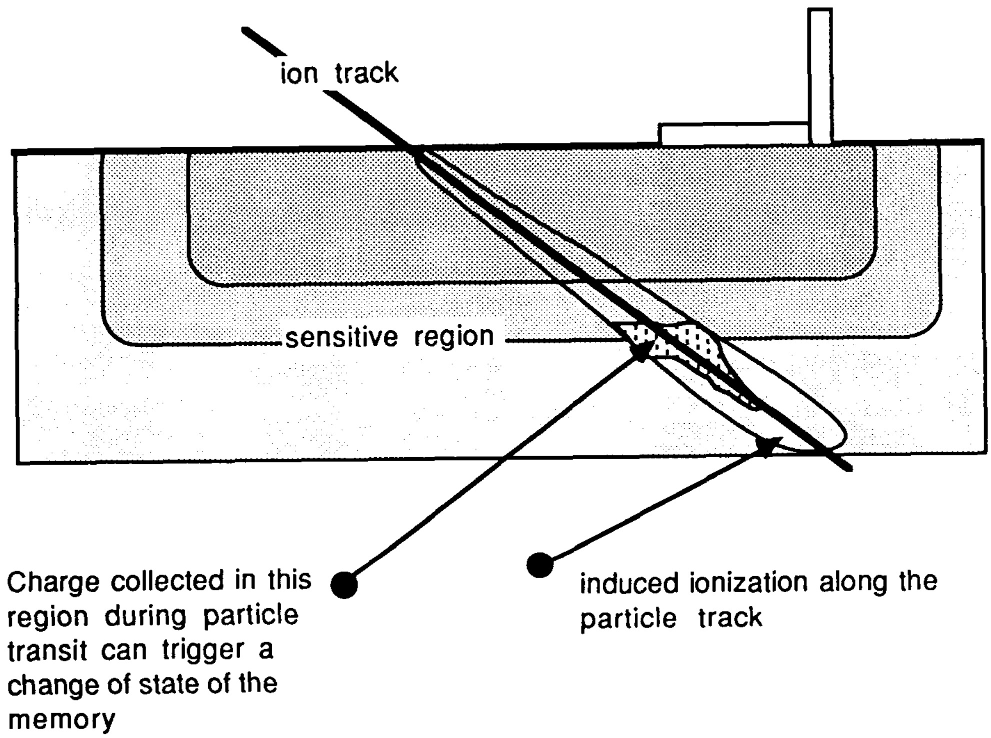
As can be inferred from this table, each ion species needs to be considered individually. Notice that the total dose effects of all heavy ions are small compared to the total dose of protons or electrons. This is because the number of other species are much smaller than either electrons or protons. Shielding is many times used to eliminate or reduce to acceptable levels total dose effects.

Single Event Upsets

A more recent perturbation to space systems is the phenomenon called single event upsets. In this case, a single particle, by depositing a short but intense charge trail, is able to change the state of a memory device. In the figure below, this is pictured as a single particle depositing enough energy in the depletion region of a bipolar integrated circuit (IC) to cause the flip-flop circuit, of which this is part, to change state (a "bit flip"). It is the combination of small feature size, high speed electronics, with dense ionization tracks by heavy ions, which leads to this phenomenon.

figure: Basic SEU Mechanism

Single Event Upset Mechanism

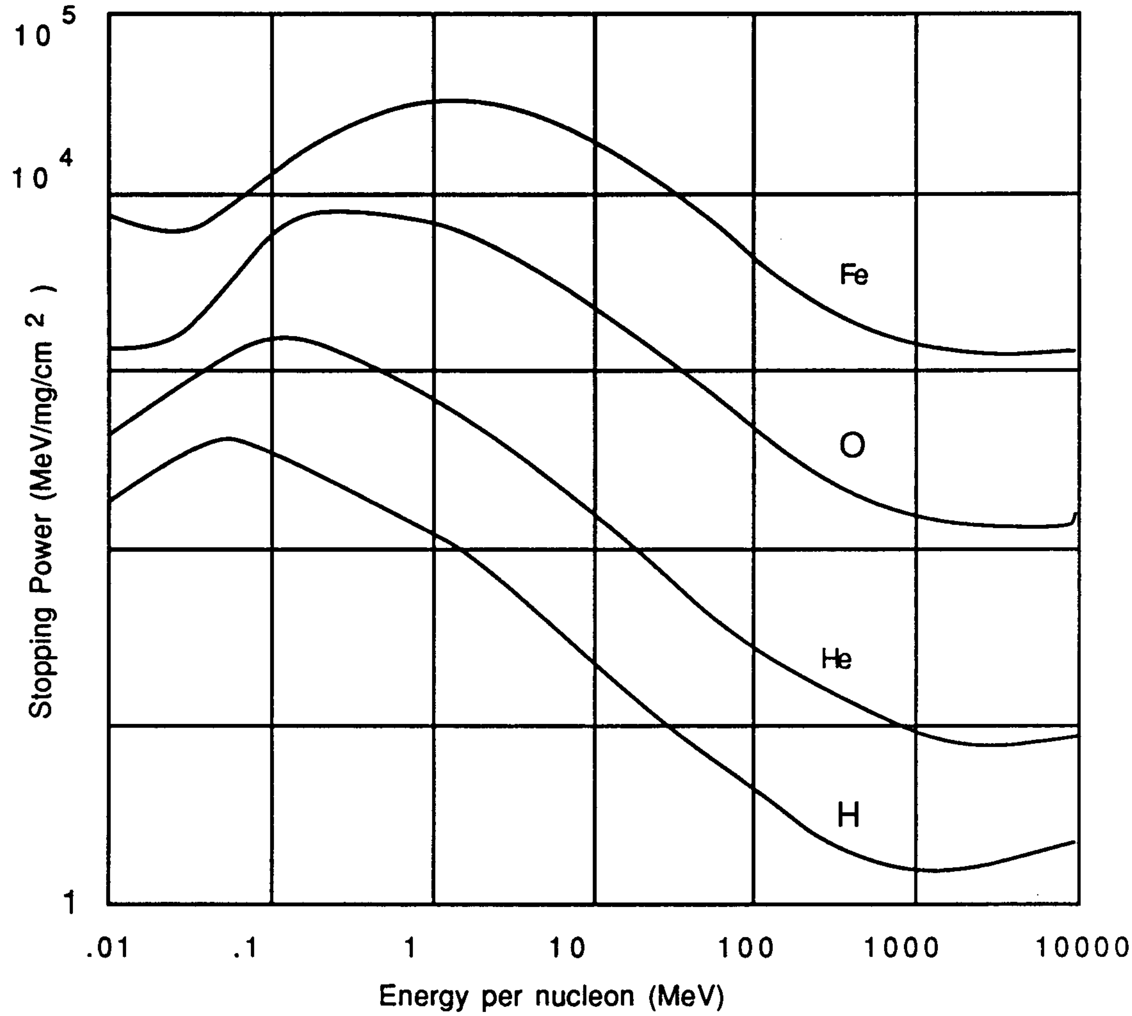


Sensitive region is typically the depletion region, although charge can be collected a considerable distance from the depletion region.

Importance of Heavy Ions

The reason that heavy ions are of principal concern for single event upsets is seen in the next figure. For a single particle to cause an upset, the charge or energy deposited in the thin depletion region of the device needs to exceed a certain minimum. Thus a high stopping power (dE/dx) or high linear energy transfer (LET) is required.

figure: Stopping Power of Heavy Ions in Silicon



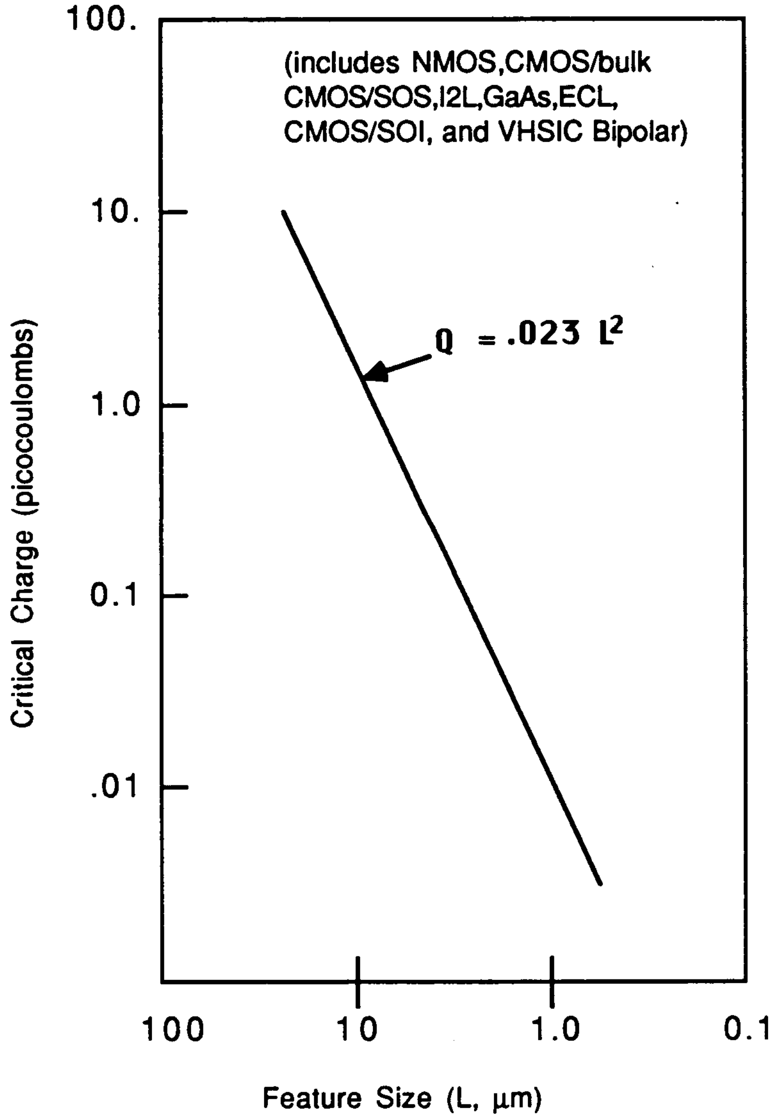
Feature Size Progress

IC (Integrated Circuits) development is tending towards faster logic and lower power. ICs are made faster and more energy efficient by decreasing the size of the features that make up the flip-flop circuit. This amounts to designing ICs in which the charge required to store information is smaller and smaller. As the charge per bit required to store information decreases, the amount of charge needed to cause a change in the stored information also decreases. The diagram below illustrates this trend. The charge used in storing information and the likelihood of upsetting the flip-flop are both related to the ability of a particle to deposit charge in the sensitive region of the device. In its simplest terms the probability of causing a SEU is a threshold phenomenon. All particles with an LET greater than a given amount normally incident on the sensitive volume will cause an upset. (Detailed calculations consider angular distributions, the structure and geometry of the sensitive volume, charge collection mechanisms, and circuit timing, in arriving at a SEU rate.)

figure: IC Feature Size

SEU Critical Charge versus Feature Size

(supplied by Petersen, 1987)



Trends in IC Development

It is unlikely that this push towards smaller, less power consuming, and faster devices will abate in the near future. Future planetary exploration needs the low power requirements, increased capability and performance these devices offer. Therefore future systems designs will need to confront single event phenomena.

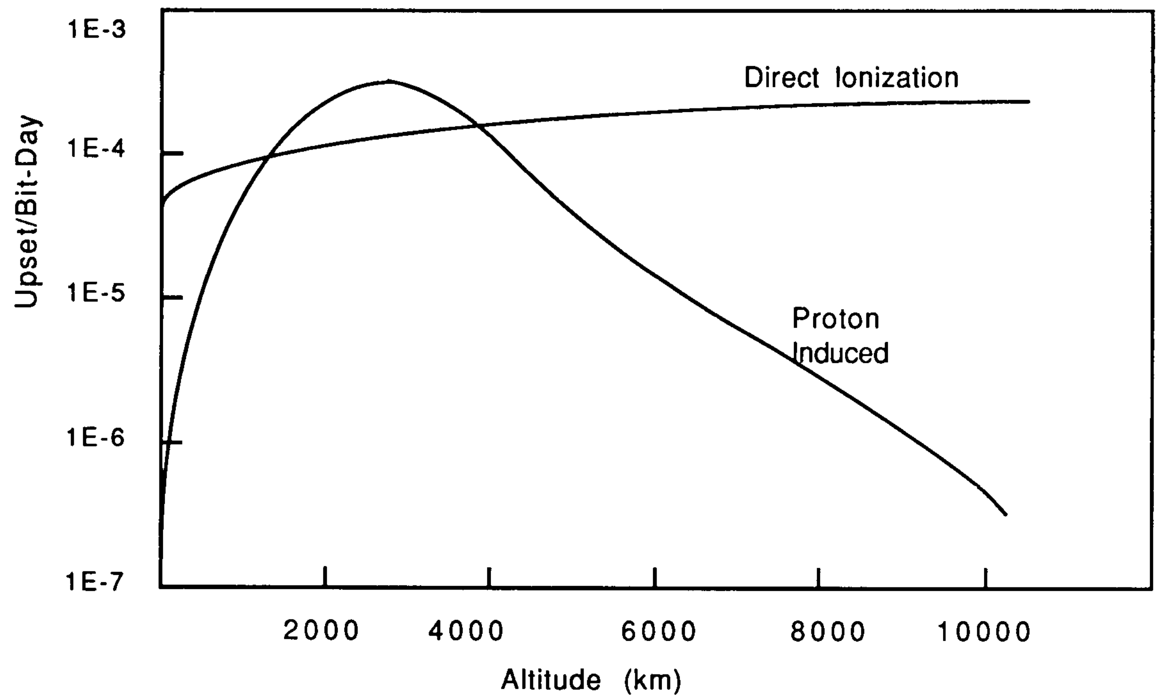
Environmental Concern

Since the concern is for high LET particles which can deposit a large amount of charge in a small sensitive volume, the environmental interest is on galactic cosmic rays and heavy ion rich solar flares. The interest is high in the CNO group and above with energies of 2 MeV/nucleon or greater. For example, the particular parts of interest to the Magellan program have sensitivities beginning around 40 Mev-cm sq/mg. Thus they have a particular interest in elements above the iron group.

Protons or other ions can cause SEUs indirectly when they create higher LET particles via nuclear reactions very near or in the sensitive volume. However, since the cross section for nuclear reactions is small, the proton or other population must be very large for this effect to be important. The figure below illustrates a typical SEU sensitive part prediction. In this case the threshold is low enough to allow proton interactions in the silicon of the chip to cause SEUs. The earth's proton belt is intense enough to make a significant contribution to the total SEU rate over a considerable region of space near earth.

figure: Typical SEU Rate Prediction

SEU Rates for AMD2901B, after Adams, 1986



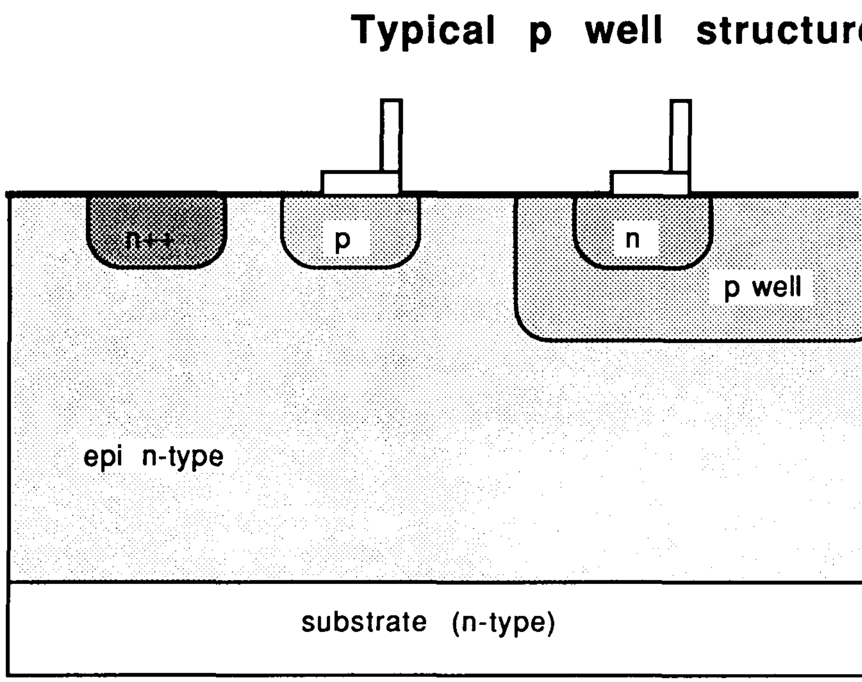
Latchups

Perhaps the primary motivating factor for calling this conference at this time is a concern on the part of several JPL planetary programs for a recently raised concern for single particle induced latchups in modern electronics. Latchups caused by over-voltage or large "gamma-dot" conditions have been known for a long time.

Single Particle Latchups

More recently, it has been shown that single high Z particles can turn "on" part of a integrated circuit in an unintended "latched" condition. Once in this state, electronics are no longer controlled in the way the designer planned, and must be powered down to regain control of the circuit. In addition it is possible for the unwanted circuit to draw enough power through the chip to damage it. Latchups occur when unintended circuits are turned on by a heavy ion. In a typical CMOS geometry these circuits cannot be avoided, although careful designing (guard rings, controlling epi layer thickness etc.) can eliminate or mitigate the problem. The figure below shows a typical CMOS structure. The unwanted "device" which latches up in this example is a pnpn structure which occurs between Vdd and ground. This will occur whenever one has a p well near devices in the n substrate.

figure: typical CMOS structure

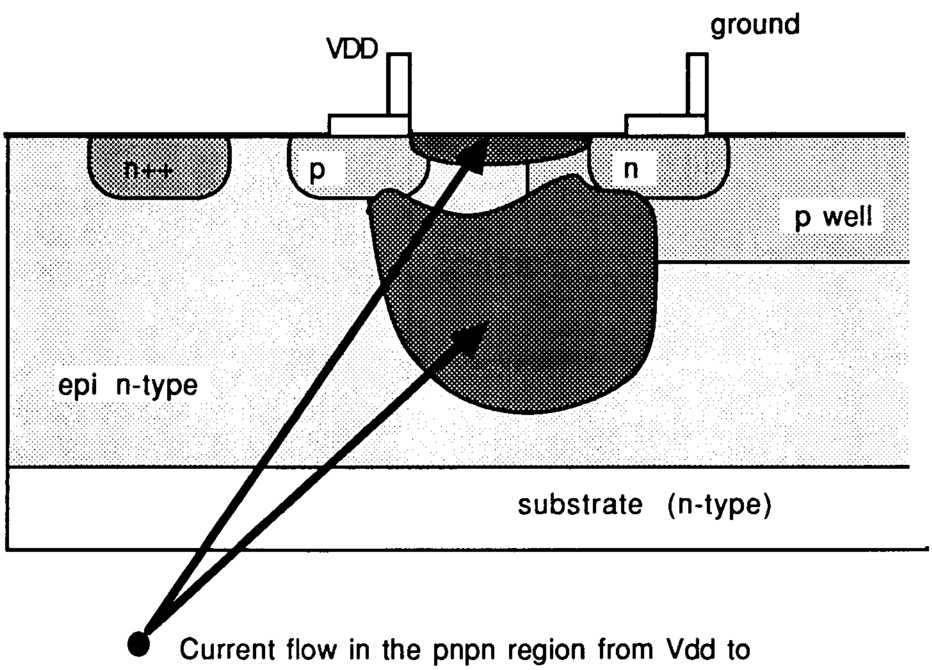


Latchup Mechanism

The current flow in the latched condition is probably quite complex. This is illustrated in the figure below. Some designers consider the pnpn structure to be coupled npn and pnp transistors such that the net gain for the circuit is greater than one (see Troutman). However, this has not been proved. Others consider multiple current paths through the structure which result in large current flow. Apparently multiple current paths are required to set up the conditions which allow the latchup condition. In spite of the fact that the detailed mechanism is not completely understood, latched conditions do exist, and have been triggered by single particles in tests.

figure: latchup circuit

SCR action initiated by single particle



Current flow in the pnpn region from Vdd to ground is uncontrolled

Causes

There are several different ways in which an inadvertent circuit can be activated in a CMOS structure. Three methods of inducing a latchup and a brief description of each are given below:

Single Particle

Single particle induced latchups are similar to a SEU. This could be a limiting factor for Magellan since the part could be destroyed or seriously degraded. For Magellan the interest is concentrated in the Fe group and above. Concern for ions below iron in Z stems from considerations of particles that enter the sensitive volume at grazing angles.

Gamma Dot

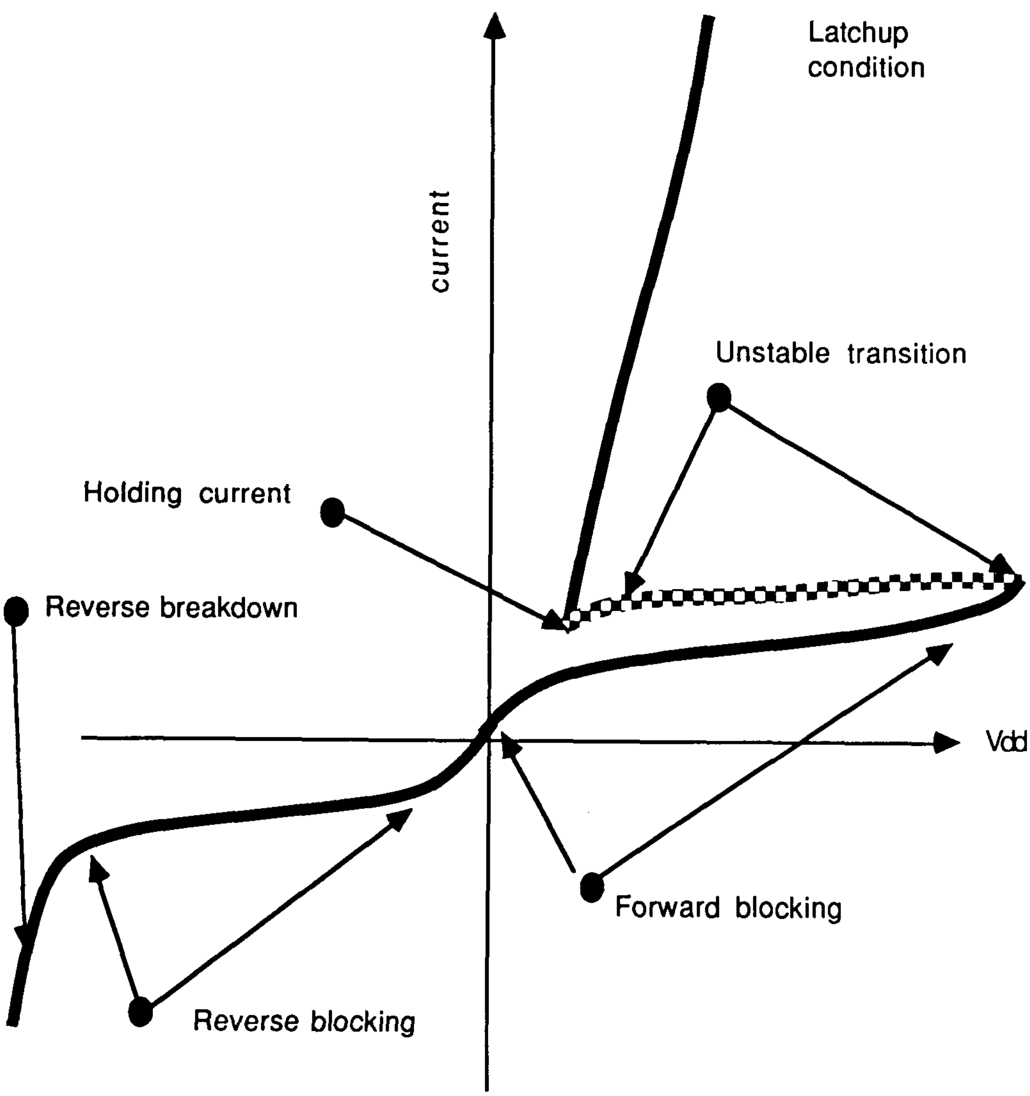
This is of concern to those who plan to survive a nuclear attack when a sudden flash of x-rays completely "disorients" the chip. Voltages and voltage differentials are uncontrolled on the chip for a short period. When the voltages settle down it is possible for the chip to be in a latched configuration.

Over-voltage

This is a well-known electronic effect where an external voltage forward biases the p-well boundary and causes the IC to fail. This kind of latchup may or may not be identical to the single particle caused latchup. The electrical characteristics of a latchup are shown in the figure below. The parts of the curve closest to the voltage axis are the normal operations of the pnpn structure in which the diodes are essentially blocking the current. However for large backward bias or forward bias, large (generally unwanted) currents can flow. The dashed portion of the curve is inferred from the existence of the holding current. If the power supply providing Vdd cannot supply at least the holding current, the circuit will drop out of a latched condition. This fact is used in some designs to prevent latchups. In other cases, resistance in the power circuits limits the current to levels which the part can tolerate. Current limiting may prevent damage to the part, but the power will have to be removed and reapplied for normal operation of the part. It is not clear without calculations or experiments what if any damage will result to a part in a latchup state.

figure: Electrical Characterization

Latchup circuit characteristics



The latchup condition is usually unintended and can result in burn out of the transistor. It always involves a pnpn or npnp situation, and can be initiated by over-voltage, a single particle, or flash x-rays.

Current Status In the Engineering Community

In single event processes it is usually the charge deposited in the electronic part that is the most significant physical parameter. This means that the environment of concern is the high energy heavy ions. Both solar flares and galactic cosmic rays include particles of this sort. This has awakened a considerable interest in the engineering community for a quantified understanding of the variability and uncertainty in the measured and predicted heavy ion environment. In particular there is a desire to understand how frequently systems will be faced with single particle events of engineering importance. The pace of development in the electronics industry is rapid enough that parts will not always be immune to single particle effects. This underscores the importance of knowing the likelihood of significant single particle events.

Currently, engineering models are "worst case." This means that the largest flux estimates and highest occurrence frequencies are used for mission assessments. The danger of overestimates is the avoidance of missions important to planetary exploration, overly pessimistic risk estimates, underutilization of modern technology, and unrealistic demands on part designs. The danger of underestimates is possible mission failure.

Environmental Models Used in Calculations

There are two kinds of environmental models used in SEU and latchup calculations. One describes the worst possible environment and its frequency of occurrence, and the other describes the environment averaged over the mission duration.

Worst case

Worst case models are very useful for "bullet proof" designs. If the environment cannot be any worse than a given model, and the system can tolerate that condition, then the system design has properly considered that environment.

Nominal

For all missions the total expected fluence is used to set electronic part design limitations. A nominal environment includes the uncertainty in the modeling and the natural variability of the environment.

The Magellan Question

Background

At this time (January, 1987), a vital memory chip in the Magellan system can "latch up" when struck by heavy ions. (Since the conference it was determined that the part failed a short time after latching, and that other problems in addition to the latchup problem made that part unusable. That part has been replaced with one which has a much reduced sensitivity to latchup.) Other missions will also face a choice between proceeding with the latchable parts (perhaps the most economical and simple choice) or redesigning the system with new non-latchable parts (and accepting the risks to costs and schedule). Both options have to be considered. Therefore it is vital to have accurate estimates of the SEU or latchup causing environment.

Latchup rates

The latchup rate is calculated by integrating a cross section as a function of LET (linear energy transfer) over the spectra of particles in exactly the same manner as SEU calculations.

The Environments

We believe the heavy ion particle spectra for Magellan will consist of the galactic background plus an occasional contribution due to large solar flares. If the background rate, due to small solar flares and galactic cosmic rays, is large enough, new parts will be needed. Thus, we need your opinion on the magnitude and variability of the background environment, particularly ions with E> 2 MeV/nuc and Z>20.

We also believe that a large solar flare rich in heavy ions would dominate the latchup rate for a day or two. If the background rate is small, a possible system solution would be to fly a detector which would safeguard the system in the event of a large solar flare. No latchups occur when the system is turned off. No data is taken with an off system, so we desire as short an off period as possible. We need to understand if a "detect and avoid" strategy is likely to work. (Contributed ideas on detectors are also desired in case such an option is chosen.)

Engineering Models

What is needed for Magellan or other programs is an engineering model, not a detailed scientific model which illuminates the underlying mechanisms. We have been thinking in terms of simple spectra of the form

$$\frac{dJ}{dE} = A\,e^{-g}$$

where A is the "magnitude" of the spectra, g (the exponent of E) describes the "shape" of the spectra, E is the energy in MeV/nucleon, and dJ/dE is the flux in particles -nucleons per (centimeter squared - second - steradians - MeV)

Example

Using the models in the references below a simple comparison of models/experience might be as follows:

Model	Fe/O	A	g	Occurrence
C	1.2 to .8	?	2.5 to 4.5	1 in 11 years
A-m	.13		2.9-5.3?	24 in 7 years
A-wc	.4		2.9 - 5.3 ?	1 in 7 years
M	.11 to .06	?	2 to 3 ?	

(!) Fe/O is the iron to oxygen ratio

A is the magnitude parameter in the simple fit in particles/(cm**2-ster-sec-(Mev/nuc)) at 10MeV/nucleon

g is the shape parameter in the simple fit (E is the energy in MeV/nucleon)

occurrence is the number of such flares per year

C is the Chenette model

A - m is the mean model from Adams

A-wc is the worse case model from Adams

M is the McGuire model

The Questions

We would very much appreciate your thoughts on our situation and particularly the following questions:

Background flux

1. What model should be used for the background heavy ion flux?
2. How variable is the "background" heavy ion flux?

Solar Flares

1. What model(s) should be used for solar flares?
2. How frequently can a significant flare be expected?
3. How variable is the solar flare flux?
4. How far in advance can solar flares be predicted/ detected reliably?
5. Will the planet Venus shield the spacecraft from a solar flare when the spacecraft is in eclipse?

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