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EFFECTS OF SPACE RADIATION ON ELECTRONIC MICROCIRCUITS

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INTRODUCTION

Originally, as the title of my talk implies, I was going to discuss briefly the cumulative effects of radiation dose on integrated microcircuits and then cover in some detail the instantaneous Single Event Phenomena (SEP) associated with energetic, individual particles (protons or heavier ions) striking the device sensitive region(s). However, since Jim Raymond has covered in admirable fashion the subject of total dose effects in his talk yesterday, it would be presumptuous and ill-advised on my part to belabor the subject; instead, I shall avail myself of the opportunity to address topics which are more closely related to the work I am currently involved in. Before leaving the subject of total dose behind, I would like to mention that because of the large populations of energetic protons and electrons in the radiation belts, displacement damage in solid state devices can play a larger role here than in other regions of space. Furthermore, the penetrating nature of the trapped radiation precludes in general the use of shielding as a means of mitigating total dose damage.

Without further ado, let us now turn to single event effects or phenomena (SEP), which so far have been observed as events falling in one or another of the following three classes:

1. Single Event Upset (SEU),
2. Single Event Latchup (SEL) and
3. Single Event Burnout (SEB).

Single event upset is defined as a lasting, reversible change in the state of a multistable (usually bistable) electronic circuit such as a flip-flop or latch. In a computer memory, SEUs manifest themselves as unexplained bit flips. Since latchup, as discussed yesterday by Jim Raymond is in general caused by a single event of short duration, the "single event" part of the SEL term is superfluous. Nevertheless, it is used customarily to differentiate latchup due to a single heavy charged particle striking a sensitive cell from more "ordinary" kinds of latchup. Single event burnout (SEB) refers usually to total instantaneous failure of a power FET when struck by a single particle, with the device shorting out the power supply. Needless to say, an unforeseen failure of this kind can ba catastrophic to a space mission.

SINGLE EVENT PHENOMENA: EARLY HISTORY

Figure 1 is a summary of the early events leading up to and resulting in our preoccupation with SEP. During the early 1960's, reverse-biased silicon diodes came into widespread use as nuclear particle detectors both on the ground and in

Early History

- 1962
  - UPSET BY COSMIC RAYS PREDICTED
- 1975
  - UPSETS OBSERVED ON INTELSAT IV
- 1978
  - UPSETS PRODUCED BY BEVELAC IRON BEAM
  - PAPERS ON COSMIC RAY UPSET PUBLISHED BY SEVERAL GROUPS
- 1979
  - RESULTS OF EXPERIMENTS ON PROTON AND HEAVY ION ACCELERATORS REPORTED BY SEVERAL GROUPS
  - REPORT ON UPSETS INDUCED BY ALPHAS FROM RADIOACTIVE DECAY

Figure 1. Early History of SEP.

space. The particle-detection process depends on the fact that an energetic ion, while passing through the depletion region of a reverse-biased p-n junction, generates electron-hole pairs along its track. These are swept out of the region by the electric field across the junction and produce a current pulse at the diode output. The amount of charge collected at the output is proportional to the energy lost by the particle in passing through the junction.

In 1962, Wallmark and Marcus[1] made the logical deduction that the same physical process which allows nuclear particle detection by semiconductor devices could lead to a spurious response by ever smaller silicon devices being used with increasing frequency in space systems. They correctly predicted that the problem would emerge when device miniaturization reached a certain critical level beyond which circuit elements would become sensitive to spurious charge

pulses created by the passage of heavy cosmic rays through vulnerable regions. D. Binder and coworkers[2] reported observations of upsets in JK Flip-Flops on board Intelsat IV. After a careful study they attributed these upsets to cosmic rays. In 1978 upsets of dynamic RAMs in space were reported by Pickel and Blandford[3] who explained the observed upset rate in terms of the known cosmic ray environment and its effect on the devices in question. Later that year Kolasinski et al [4] simulated directly the effect of heavy cosmic rays on solid state memories with the use of a very energetic iron beam from the Lawrence Berkeley Laboratory (LBL) Bevalac accelerator. They continued the work in 1979 using the 88-in. Cyclotron at LBL and discovered SEL in the process[4]. In approximately the same time frame investigators at the Naval Research Laboratory[5] and the Air Force Geophysical Laboratory[6] were actively studying upsets caused by protons with energies like those of protons trapped in the inner Van Allen belt. Since that time, numerous manifestations of the various SEP have been observed in semiconductor devices both on the ground and in space-borne systems. Figure 2 is a summary of

SEU Rates in Space

UPSETS PER 10^6 BITS PER DAY
(COURTESY OF E.C. SMITH, HUGHES AIRCRAFT CO)

PROGRAM	PART TYPE	RATE
INTELSAT IV	J-K FLIP-FLOP	16.0*
PIONEER VENUS	PMOS SHIFT REGISTER	7.0
PV/EO	SCHOTTKY TTL 64 BIT RAM	12.0
EO	MISC ANOMALIES	10.0
GPS	4096 BIT NMOS RAM	10.0

Fig. 2. Observations of SEU in Space.

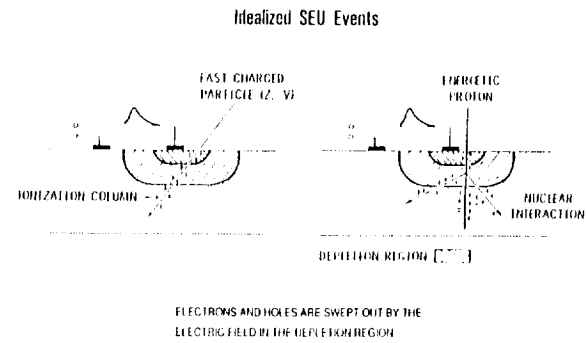

Fig. 3. Pictorial View of the SEP Process.

some of the early observations of SEU in space. An excellent review of the early days of SEP studies, together with a bibliography up to 1982 has been written by Sanderson et al.[7].

THE NATURE OF SINGLE EVENT EFFECTS

When considering any single event effect associated with an integrated circuit chip, it is important to keep firmly in mind the instantaneous and microscopic nature of the underlying process. In other words, the time during which charges are generated in the sensitive region is negligible compared with the time for charge collection; also, the initial diameter of the charge column is smaller than or comparable to the size of the sensitive region. This is in contrast to other common radiation effects such as cumulative total dose damage or response to a short burst of flash x-rays or particles, where the whole chip is bathed in radiation.

Figure 3 above depicts in schematic form the essential features of the mechanism responsible for SEP. At left on Fig.3, a heavy ion traversing the reverse-biased junction depicted on the chip produces a dense track of ionization (electron-hole pairs). The charges move to the electrodes under the electric field within the so-called depletion region, which to first order is the sensitive region for SEU. Upon being collected, the charges produce a current pulse at the circuit node. The linear charge density along the track is proportional to the rate at which the particle loses its energy, or its "linear energy transfer" (LET) in technical jargon. The higher the particle LET and track length within the sensitive region, the higher the deposited charge and hence the node current which may result in a single event upset or other phenomenon.

An upset occurs when a certain minimum amount of charge (the critical charge) has been collected at the circuit node in a time small in comparison with the circuit response time. Generally this prompt charge-collection time is in the pico-second domain, while the circuit time constants are measured in nanoseconds. The circuit critical charge divided by the longest dimension (track langth) within the sensitive volume is defined as the threshold LET for a given SEP.

On the right hand side of Figure 3 we see a somewhat different phenomenon taking place. Here, an energetic proton like those trapped in the radiation belt collides with a silicon nucleus within the depletion region, and a nuclear reaction in the form of scattering, neutron emission, fragmentation etc. takes place. As we shall see in a moment, the proton LET is too low to produce enough current for an upset, but by transferring its energy and momentum to the nuclear reaction products whose LET is much higher, the proton can produce an upset. Clearly, the lower the threshold LET of the device for upset with heavy ions, the more vulnerable will the device be to upset by protons. Since the trapped radiation zones contain large fluxes of energetic protons, spacecraft traversing these zones are subject to an increased rate of SEP.

Figure 4 summarizes the process of ion interaction with matter. As we can see, dE/dx and hence LET varies as the

square of the nuclear charge (atomic number) and inversely as the square of the ion velocity. The table at the bottom of

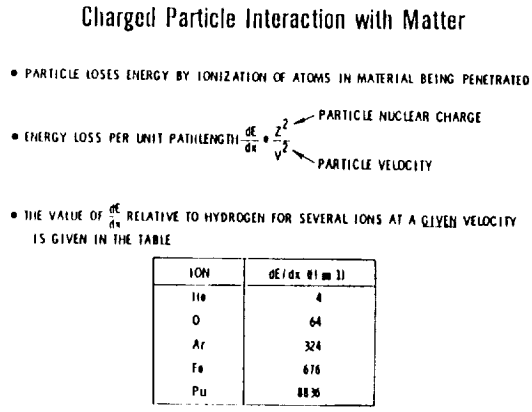

Fig. 4. Ion Interaction with Matter.

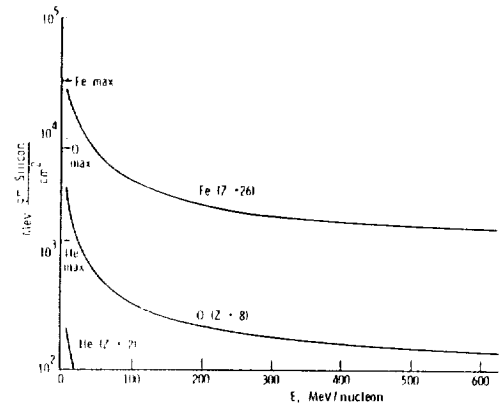

Fig. 5. Energy Dependence of LET.

Figure 4 shows the LETs of several ions relative to protons. We see that the linear charge density along an iron track is almost 700 times that produced by a proton with the same velocity. The increase of LET with increasing atomic mass can be shown more dramatically by multiplying the numerator and denominator of the expression for dE/dx in Fig. 4 by M, the nuclear mass. The denominator now becomes the ion energy, and we note that the rate of energy loss or LET varies directly as the product of ion mass and the square of its charge, and inversely with the energy. Another way of looking at the inverse-square dependence of LET on ion velocity is to remember that velocity squared is essentially energy divided by the ion mass, where the latter equals the mean bound nucleon (ie.proton or neutron) mass times the number of nucleons. Thus LET varies as the square of the nuclear charge and inversely as the energy per nucleon.

This functional form of LET is shown in Fig. 5 for the three major cosmic-ray constituents, not counting protons. Note that LET (vertical axis) is expressed here in units of MeV/(g/cm^2), ie. the energy lost in traversing a thickness of material weighing 1 g/cm^2. In some applications it is more useful to express LET in units of pC/micron. I shall leave it as an exercise for the reader to show that 1 pC/micron in silicon is equivalent to 98 MeV/(mg/cm^2). Looking at the oxygen curve in Fig. 5, we note that at 100 MeV/nucleon (1.6 GeV total energy), the oxygen nucleus loses roughly 300 MeV in traversing 1 g/cm^2 of silicon. To stop it completely would require several g/cm^2 of shielding. Thus at these energies, shielding against energetic ions in space is impractical except in a few very special cases.

SPACE-RADIATION ENVIRONMENTS RESPONSIBLE FOR SINGLE EVENT EFFECTS

Single event effects in microelectronics are caused primarily by three types of radiation environments in space: galatic cosmic rays, solar cosmic rays and trapped charged particles. While this session is devoted to the effects of trapped

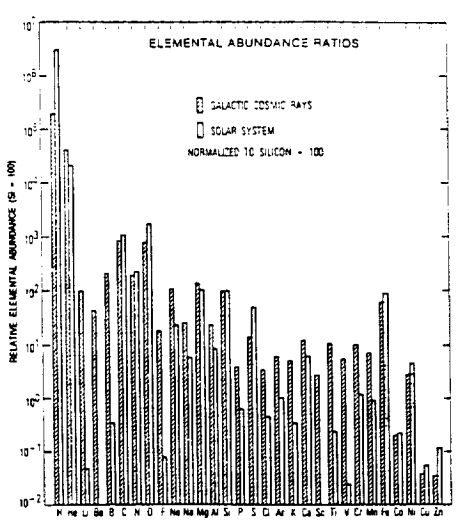

Fig. 6. Cosmic Ray Abundance Ratios.

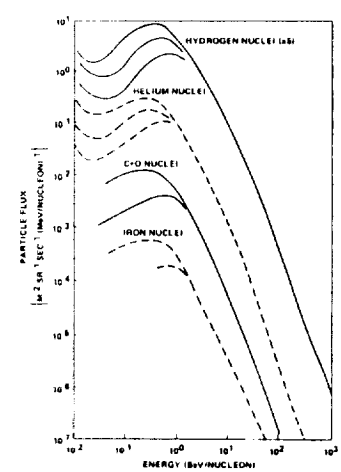

Fig. 7. Cosmic Ray Energy Spectra.

radiation, I shall briefly discuss the other two environments, since to a greater or lesser extent they coexist with the third in many regions of space and are the major contributors to SEP. In the previous talk, Al Vampola presented a very thorough description of the trapped environment, so I shall only comment briefly on its aspects pertaining to SEP.

Galactic Cosmic Rays

Figures 6 and 7, respectively, show the relative abundances and energy spectra of the galactic cosmic rays. The most prominent in this environment are protons, alpha particles, nuclei in the carbon and oxygen group and finally the nuclei with atomic numbers close to that of iron. A very exhaustive and detailed description of the environment has been given by J. H. Adams[8], including an analytical formulation and review of the experimental data on which it is based. It is important to note that the environment is most severe at spacecraft-orbit altitudes exceeding a few thousand kilometers. At lower altitudes and inclinations below approximately 50 degrees, the earth's magnetic field keeps out a large portion of the low to medium energy flux of the heavy ions. In the polar regions, however, these ions reach low altitudes by spiralling along magnetic field lines, so that the flux intensity is not reduced very much over that at high altitude.

The galactic cosmic ray intensity is modulated by the 11-year cycle of solar flare activity, with the maximum flux occurring during minimum solar activity and vice-versa. Hence the term "solar-minimum flux" refers to the highest intensity flux and so implies the most severe environment. This can be confusing to someone uninitiated to the technical jargon. The degree of solar cycle modulation of the flux is shown by the branches in the spectra of Figure 8.

Solar Flare Particles

An example of heavy ion fluxes associated with a solar flare is shown in Fig. 8. Since solar flares occur sporadic-

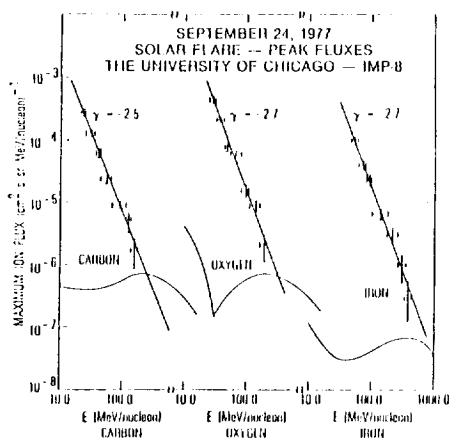

Fig. 8. Particle Fluxes in a Heavy Ion Rich Solar Flare.

ally, so does the associated environment. As in the case of galactic cosmic rays, it is the energetic charged particles, accelerated near the sun during some solar flare events, that cause single event phenomena and total dose damage. Our understanding of solar activity is too rudimentary for us to be able to predict far in advance the exact onset time of a solar flare. Individual flare occurences appear to be quite random, except that their frequency follows the 11-year sunspot cycle mentioned above.

Most solar flares produce proton fluxes which do not contribute significantly to the single event rate. Generally, the flux of the heavier ions in those flares also is not very significant. However, as the example in Fig. 8 shows, flares rich in heavy ions do occur sometimes, and the flux of medium energy heavy ions from such a flare can exceed the galactic background by more than one order of magnitude. Finally, a "monster" flare like the one in August, 1972 can cause general havoc in spacecraft systems. It is indeed fortunate that these events are rare and of relatively short duration (a few hours to a day or so). A summary of recent solar flare environment data of interest in single event effects work has been published by Chenette and Dietrich[9].

Trapped Particles

In regions around the Earth, only the inner Van Allen belt is of concern, and even then only for devices with relatively low degree of immunity against single event effects. The trapped proton flux in the inner belt is many orders of magnitude higher than the flux of galactic cosmic rays. However, as was pointed out above, protons can cause single event effects in currently available devices only indirectly, by way of nuclear reactions in or near the device sensitive regions. Since the probability of these reactions taking place is extremely small, only a few of the devices currently used in space are vulnerable to proton induced single effects. More will be said on this subject later.

EXPERIENCE IN ORBIT

Early observations of SEU on various spacecraft with payloads containing MSI and LSI devices have already been shown in Figure 2. Here the data all seem to cluster around an upset rate of approximately 1 upset per day for a 100,000-bit memory and the rate does not appear to depend strongly on the device technologies used in the various spacecraft.

More recently, Blake and Mandel[10] have published upset rates in CMOS/bulk RAMs on board a spacecraft in a low altitude, polar orbit. The observed rate of approximately 3×10^{-7} per bit per day is considerably lower than the values appearing in Figure 3. At the other ond of the scale, upset rates in the neighborhood of 3×10^{-3} per bit per day have been observed in low power bipolar RAMs on board the LEASAT vehicle[11].

Upsets have also been observed in devices flown by the NASA Goddard Space Flight Center on the Space Shuttle as part of the Cosmic Ray Upset Experiment (CRUX). The payload flew in an orbit with 57 degrees inclination. It contained complements of VLSI, NMOS dynamic and static RAMs, as well CMOS non-volatile PROMs. No upsets were observed in the PROMs, while the RAM SEU rates fell in the range of 10^{-7} - 10^{-6} upsets per bit per day. Clearly, there appears to be a large range of vulnerability to SEU among the various device technologies.

SUMMARY OF GROUND-TEST AND MODELING ACTIVITY

In view of the fact that the severity of single event effects in space can range from inconsequential to catastrophic,

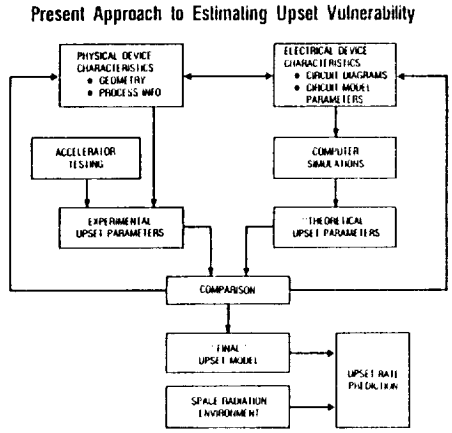

Fig. 9. Flowchart of Modeling Effort.

it is not surprising that during the past decade considerable effort has been expended in testing, modeling and hardening devices against single event effects. The ultimate objectives of these efforts are to acquire the capability of predicting the single event effect rates in orbit for commercially available devices, to harden existing payload designs wherever feasible, and to develop new device technologies resistant to single event effects. Attempts to attain these objectives have concentrated on device modeling, circuit analysis, ground testing of devices and test structures, and acquisition of on-orbit data. This work is briefly summarized below. Figure 9 is an idealized flow-chart of the activities which result in a prediction of single event rate in space.

The parameters absolutely necessary for predicting the single event rate are the minimum charge(s) needed to induce a single event such as an upset, the geometry of the sensitive region(s) and the charge-collection efficiency at the relevant circuit node(s). Because of the fast and microscopic nature of the single event process, circuit parameters like the critical charge or the current-pulse shape cannot be simulated and measured with conventional electronic test equipment.

Instead, theoretical computer models of field configuration and current flow originating from the ion track are developed and used to determine the extent of the sensitive region and minimum charge density along the ion track needed to initiate a particular type of single event.

Ground tests are then performed to validate the model predictions of minimum charge density and probability of upset (SEU cross-section) in the ion beam. Figure 10 summarizes in schematic form the test activities and type of data ob-

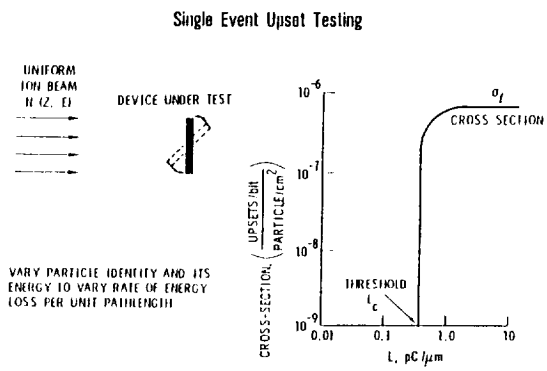

Fig. 10. Summary of Test Procedures.

tained. The devices under test are placed in a uniform beam of protons or heavy ions and exercised in appropriate fashion while being irradiated. The number of bit errors or other upsets, as well as the beam fluence, are recorded and the the cross-section computed using the expression

$$\sigma_L = N\sec(\theta)/F,$$

where σ_L, N, θ and F are, respectively, the upset cross-section in cm^2, number of errors, beam angle of incidence with respect to the chip-surface normal and the total beam fluence in particles/cm^2.This process is repeated at various angles of beam incidence and with particles having the range of LETs needed to determine the threshold value of LET. More often than not, the parts have to be de-lidded in order to allow the ions to penetrate into the sensitive region of the device.

After one or more iterations of theoretical simulation and ground testing, heavy ion upset rates are predicted for specific environments using computer programs like J. C. Pickell's Cosmic Ray Induced Error (CRIER)[12] or J. Adams' Cosmic Ray Upset Model (CRUM)[13] codes. In these calculations, LET spectra for orbits of interest are first generated in the presence of shielding appropriate for the payload under consideration. The dimensions of the sensitive regions and critical charges for upset, generated in the modeling and test efforts are then provided to the programs which generate random path-length distributions and determine which particles within the calculated LET spectrum deposit enough charge to induce the single event effect.

Petersen et al.[14] have developed a simple and useful expression for estimating the upset rate of microcircuit memories in the so-called "10 percent worst case" galactic cosmic ray environment of Adams[8]. The upset rate R, measured in upsets per cell per day, is computed from the expression

$$R = 5 \times 10^{-10}\sigma_L/L_c^2,$$

where σ_L is the upset cross-section expressed in square microns and L_c is the critical LET expressed in pC/micron. This useful "Figure of Merit" is valid in regions of space where the galactic cosmic ray environment is not significantly affected by the Earth's magnetic field. In regions where trapped radiation is dominant, upsets due to galactic cosmic rays will be in general less, and the contribution from trapped protons has to be computed.

We have seen that proton upsets are induced indirectly via nuclear reactions and so the techniques outlined above for calculating heavy ion upset rates in space do not apply in the case of protons. A semi-empirical method for estimating proton induced upsets in spaceborne memories has been developed by Bendel and Petersen[15]. Upon examining trends in proton test data obtained on a large variety of devices and reconciling these trends with nuclear reaction data at the low and high proton-energy extremes, they came up with a rather simple and elegant equation for the proton-upset probability or cross-section which depends on just two variables, viz. E, the proton energy and the parameter A which is equivalent to the apparent threshold at low energy. Their result is shown in Figure 11, plotted as a function of proton energy for various fixed

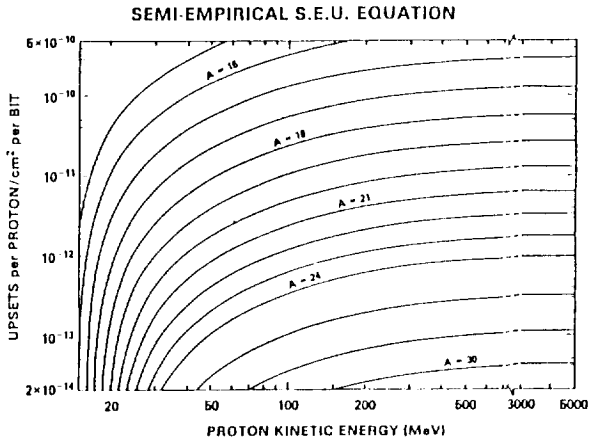

Fig. 11. Bendel and Petersen Model.

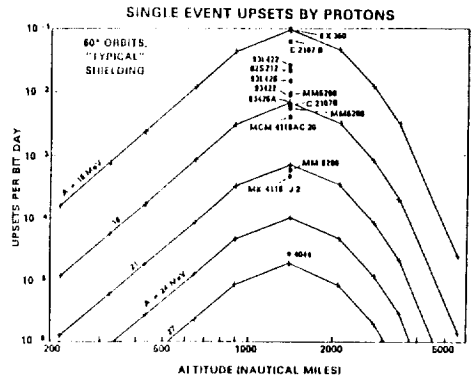

Fig. 12. Predicted Proton SEU Rates.[15]

values of the parameter A. Note that in this model, the measurement of the upset cross-section at a single proton energy significantly above threshold is enough to determine the device upset cross-section at all energies and hence the upset rate in any given proton space environment. Figure 12 shows the upset rates predicted by Bendel and Petersen for some devices flying in a 60 degree inclination orbit, at 1400 nm altitude. In Figure 13, the proton SEU rate in a part with A=25 MeV is

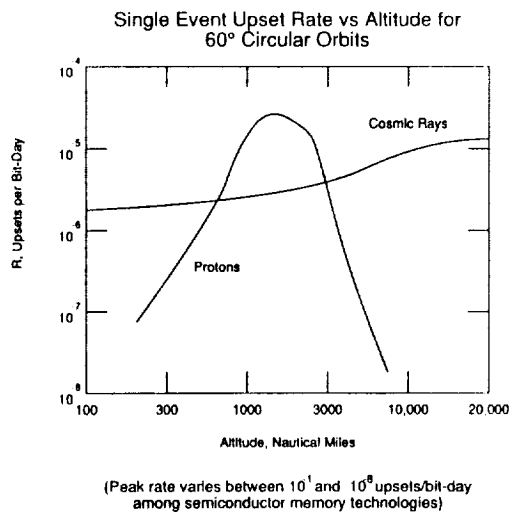

Fig. 13. Galactic and Solar Cosmic Ray SEU Rates Compared.

compared with the upset rate induced by galactic cosmic rays. In general, we would expect the trapped proton contribution to upset rate to dominate in low inclination orbits within the inner Van Allen belt, while in highly inclined orbits the rate should be comparable to the galactic cosmic ray contribution.

Validation of the model predictions is, of course, obtained from observations of single event rates in space. Unfortunately, while some data showing that the predictions are "in the right ballpark" exist, there are not nearly enough of such data, particularly of those acquired under carefully controlled conditions, so that their validity and correlation with an actual environment can be established.

In concluding this talk, I would like to give you an idea of the range of vulnerability of existing device technologies, as determined in the studies outlined above. Figures 14 and 15 show the predicted heavy ion upset rates for some representative device types in bipolar and MOS technologies, respectively. The comparisons listed in Figs. 14 and 15 are based on the Petersen et al. "Figure of Merit"[14] and do not reflect the proton induced SEU rates in the inner Van Allen radiation belt. However, devices showing upset rates of lesss than 10^{-6} per bit-day can be expected in general to be quite hard against proton-induced SEU. I base this statement on the empirical observation that devices with threshold LETs above

10 Mev-cm^2 do not in general upset with protons, while with heavy ions, according to the Petersen formula, they upset at rates comparable to or less than 10^{-6}/day.

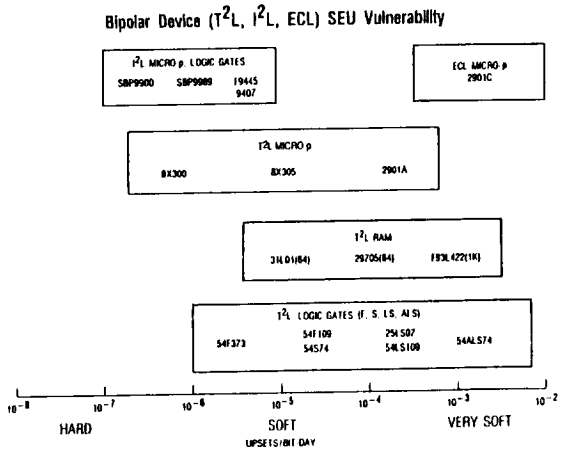

Fig. 14. SEU Rates for Bipolar Devices.

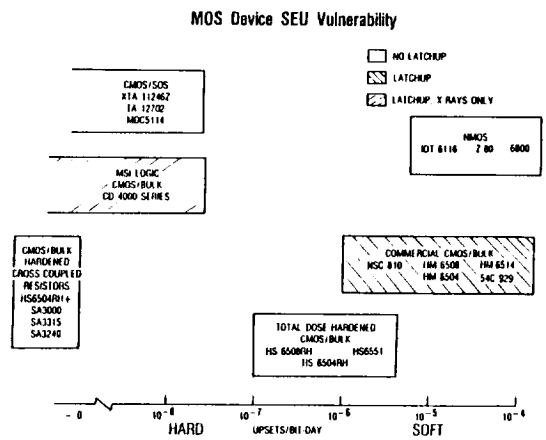

Fig. 15. SEU Rates for MOS Devices

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