NEUTRON GENERATED SINGLE-EVENT UPSETS IN THE ATMOSPHERE

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Abstract

Heavy cosmic ray nuclei are mostly attenuated with a shielding of 50 g/cm^2 atmospheric gas. However, the shielding acts as a generator of neutrons, evaporated or knocked out of nuclei. These neutrons generate highly ionizing nuclear recoils that produce single-event upsets in microelectronic components. To attenuate the secondary neutron flux over 300 g/cm^2 of atmospheric material is required. The numerous slow protons from nuclear interactions in shielding will also generate upsets in sensitive components, which have a low critical charge. At altitudes below 65,000 feet, most single-event upsets are due to these secondary particles. The upset rates due to neutrons and slow secondary protons from cosmic ray, solar flare particle, and trapped radiation particle interactions are presented as a function of the critical charge.

1. Introduction

As high-energy heavy cosmic ray nuclei are absorbed by nuclear interactions or by ionization loss, another radiation component--neutrons--that causes single-event upsets in microelectronic computer components builds up in intensity. Neutrons are extraordinarily penetrating due to the absence of ionization loss.

Energy deposition in microelectronic chips, in the case of neutrons is due to nuclear collisions[1] in, or in the immediate vicinity of the chip. Such nuclear collisions generate nuclear recoils. Ziegler and Lanford[2] calculated the recoil energies of silicon nuclei due to elastic scattering of neutrons. However, the figures of Ziegler do not take into consideration the high-energy nuclear recoils generated in nuclear spallation reactions. For example, the cross section for 1-MeV recoils generated by 10^3 MeV neutrons is underestimated about 100 times, and that of higher energy recoils by many orders of magnitude. While Ziegler and Lanford[2] estimate that recoil energies up to ~ 3 MeV contribute significantly, we find that recoil energies up to 20 MeV are important. Experimental data on nuclear recoil charge composition and energy spectra have been published by Westfall et al.[3] Our computations of the single-event upset rate are based on a combination of the elastic scattering data presented by Ziegler and Lanford[2] and our analysis of the data of Westfall et al.[3] on energy spectra of nuclear recoils.

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2. Energy Spectra of Neutrons

The flux of neutrons is nearly constant at atmospheric depths of 30 to 200 g/cm^2, as measured by Hess et al.[4] and Holt et al.[5], and calculated by Armstrong et al.[6] and Light et al.[7]. At solar minimum the flux of neutrons at atmospheric depths of 50 to 150 g/cm^2 (~ 65-50 Kft), at a geomagnetic latitude of $\lambda = 40^\circ$, in the energy interval 1 to 10 MeV is 1 $\pm$ 0.2/cm^2 sec, according to Armstrong et al.[5], and Hayakawa,[8] and references therein. Above 10 MeV, the flux is 0.6. At high geomagnetic latitudes, the flux is about 2 times higher, and near the equator, about 5 times lower. At solar maximum, the flux at high geomagnetic latitudes is about 60% of that at solar minimum, and at 40° latitude, about 75%. At geomagnetic latitude of 40°, the flux near sea level is about 200 times less than between 50 and 150 g/cm^2.

Figure 1 shows the neutron energy spectrum at solar minimum, $\lambda \approx 40^\circ$, and 50 to 150 g/cm^2. (At 30 g/cm^2 or 200 g/cm^2, the flux is slightly lower, by 20%.)

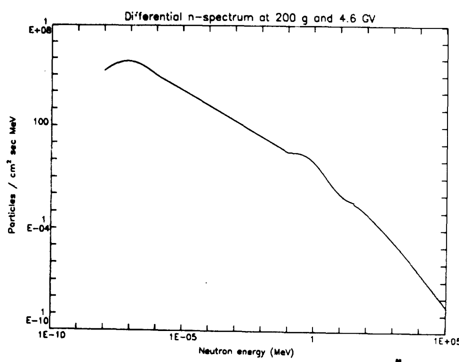

Fig. 1. Neutron energy spectrum at an atmospheric depth of 100 g/cm^2, near solar minimum, at a geomagnetic latitude of 42°.

3. Energy Spectra of Nuclear Recoils

Nuclear spallation reactions transfer a considerable amount of energy to the recoiling residual nucleus. For neutrons with energy > 1 GeV, we adopt the recoil energy spectra measured by Westfall, et al.[3] displayed in Fig. 2 for recoil nuclei 3 < Z < 5, 6 $\leq$ Z $\leq$ 9 and Z $\geq$ 10, respectively. Fig. 2 displays the differential cross sections measured at 90° in the lab system. The interpolation to lower energy neutrons was carried out using the data of Roche et al.[11], measured near 100 MeV.

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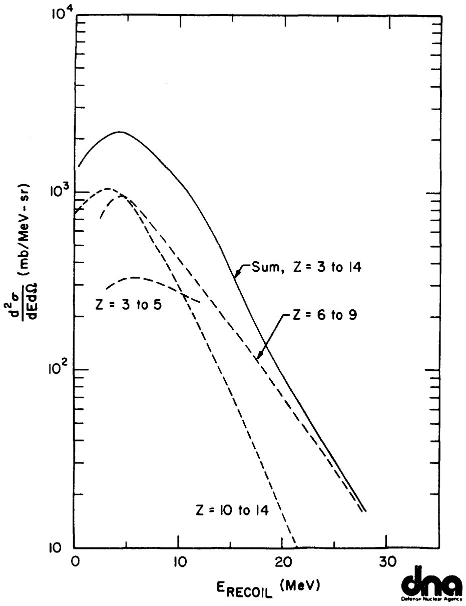

Fig. 2. Energy spectra of spallation products of Si, at 90° in the laboratory, irradiated by nucleons at E $\geq$ 1 GeV. The energy spectrum of Li, Be, B is discontinued at a range of 10μ, the adopted chip size. The spectra are based on the measurements of Westfall et al.[2], who used an Al target.

4. Burst Generation Rate

We adopt the definition of Ziegler and Lanford[2] for the burst generation rate b or charge deposition by a nuclear recoil in a chip. However, the numerical values of the burst generation rate we use includes the energy spectrum of the residual nuclei induced by spallation, discussed in the previous section. The burst generation rate is approximated by, in units of $cm^2/\mu m^3$,

$$b = 10^{-16} \exp (F_1 + F_2) \left[1 - \exp\left(\frac{E - E_{min}}{20E_b^{1.4}}\right)\right]$$

$$F_1 = 6.0 \exp -\left(\frac{E_b}{7.5}\right) \qquad (1)$$

$$F_2 = 3.2\,(0.4 - E_b^{0.5}) \exp\left[-E_b - \left(\frac{E - 10E_b}{20}\right)^2\right]$$

$$E_{min} = 7.5\, E_b^{1.1} \geq 0.4 \text{ MeV}$$

Figure 3 illustrates the burst generation rate as a function of the neutron energy for various recoil energies E_b.

5. Burst Generation Rate due to Slow Secondary Protons

In very sensitive microelectronic components (i.e., those with a critical charge < 2 x 10^{-3} pC) slow protons can generate single event upsets.

The measurements of low-energy secondary proton energy spectra have been reviewed by Hayakawa[8] and Ziegler and Lanford;[2] the corresponding dose rates have been calculated by Armstrong et al.[9] Armstrong et al.[10] have also calculated the radiation doses due to neutrons and protons generated in solar flare particle interactions.

In our calculations, we combine the energy spectrum of slow protons (E $\leq$ 30 MeV) of Ziegler and Lanford[2] with the atmospheric depth dependence given by Hayakawa[8]. The flux of slow protons with a rate of ionization loss greater than $(dE/dx)_o$, having an energy less than $E_o \leq$ 30 MeV is approximated by:

$$J[>(dE/dx)_o] = \int_{0.5}^{E_o} K \; E^{\alpha} \; dE \; (cm^2 \sec \text{ Mev})^{-1} \qquad (2)$$

where α = 1.0, K ~ 1.3 x 10^{-6} at atmospheric depths 50 to 100 g/cm^2, 6 x 10^{-7} at 200 g/cm^2 and 3 x 10^{-7} at 300 g/cm^2. Although the spectrum of protons below 30 MeV is highly uncertain, the resulting changes in the upset rate are not significant.

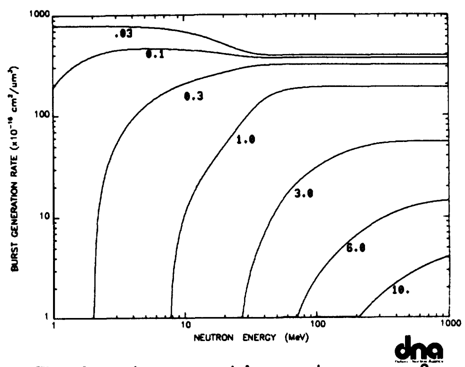

Fig. 3. The burst generation rate as a function of neutron energy for n + Si reactions. The numbers in the figure represent recoil energies E_b.

6. The Upset Rate Due to Neutrons, Secondary Protons and Pions

In the paper "Cosmic Ray Heavy Ions at and Above 40,000 Feet," by Tsao, et al.[12] the contribution of cosmic rays to the single event upset rate, at an altitude of 55,000 feet, is compared to that of cosmic-ray secondaries. The latter were displayed separately for the neutron-generated nuclear recoils, and for ionization loss of slow protons. Below 65,000 feet (or x > 50 g/cm^2), these secondary components are found to dominate.

The pion/proton ratio at 2 GeV is 0.2 near sea level, and less at higher altitudes, and at lower energies[13]. Furthermore, the more highly ionizing slow pions produced in the upper atmosphere will mainly decay into muons in flight. Thus the contribution of pions to upsets is less important.

Figure 4 shows the critical charge spectrum of the upset rate at 100 g/cm^2 of air (55,000 feet) as well as at sea level, due to neutron generated recoils and slow protons. At sea level, also the contribution of ionization losses of slow muons, based on Ziegler and Lanford[2], is shown. The latter is important only for very sensitive devices with a low critical charge.

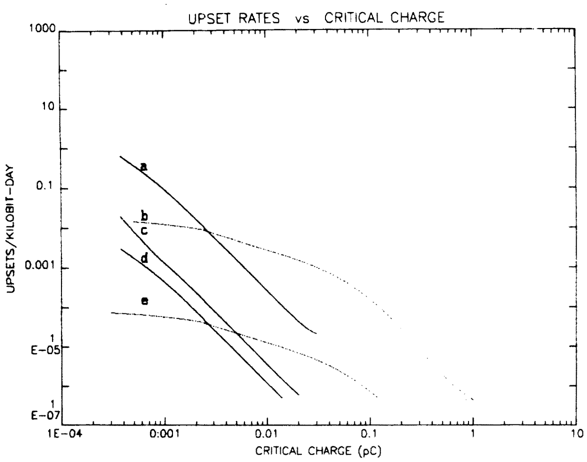

Fig. 4. The upset rates at high latitudes, at 55,000 feet due to cosmic-ray generated secondary particles: (a) slow protons, (b) neutron interactions, and at sea level due to (c) muons, (d) slow protons and (e) neutron interactions.

Figure 5 shows a comparison of the critical charge spectrum of the upset rate for (I) cosmic rays at the top of the atmosphere, (II) cosmic rays at 55,000 feet, and (III) secondaries, represented by curves a and b, from a giant flare at 55,000 feet or trapped radiation flux secondaries at 2000 miles, and x ~ 20 g/cm^2 Al. The upset rate for cases III is 10^3 to 10^4 times larger than that due to cosmic ray secondaries, though it should be remembered that such large flares occur only for a single two-day period in ~ 11 years. Due to the steep spectra of flare particles and radiation belt particles and lesser abundance of nuclei heavier than protons, the secondary contribution (for a critical charge greater than 0.02 pC, in a bit having a volume 10 x 10 x 5 μ^3) dominates already after about 5 g/cm^2 in the case of solar flares and for even less material in the case of radiation belt particles.

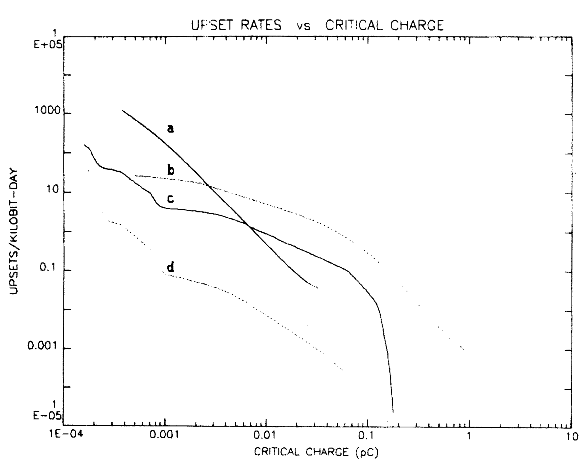

Fig. 5. The upset rate at high latitudes, at 55,000 feet, at the time of a very large flare, due to such secondary particles as (a) slow protons, (b) neutron interactions. The upset rates, due to cosmic ray nuclei (c) at 150,000 feet and (d) at 55,000 feet are shown for comparison.

Figure 5 can be used to estimate the upset rate due to smaller flares. For a flux of J(>100 MeV) protons/cm^2 sec, and a spectrum like that of the February 23, 1956 flare, curves (a) and (b) of figure 5 are scaled by the factor J(> 100 MeV)/(2.5 x 10^4).

Acknowledgement

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