Soft upsets in semiconductor memory devices can be produced by charged particles produced in nuclear reactions in the semiconductor or in its surrounding materials. We have calculated the particle production cross sections for incident neutrons and protons in various semiconductor materials in the energy range of 5 to 75 MeV. The common semiconductor elements and compounds all have approximately the same alpha particle production. There is also appreciable proton and heavy ion production which under some conditions may cause upsets.

**Introduction**

There has recently been interest in soft upsets produced by secondary alpha particles. The alpha particles can be produced by nuclear reactions in silicon from cosmic-ray produced neutrinos at ground level or from protons in space. We want to identify the nuclear reactions that produce the alpha particles in silicon, and then examine other semiconductor materials to see if they have the same likelihood for alpha production, and therefore soft upsets.

We also want to consider other reaction products, especially protons. Recently the importance of protons in inducing upsets has been pointed out by Kirkpatrick and soft upsets due to low energy protons have been observed by Wyatt. Protons have often been ignored as dE/dx for a proton is generally 1/10 that of an alpha particle of the same energy. However, when considering soft upsets in semiconductor devices, it is the energy that is deposited in some characteristic dimension that is important. For example, in a 20 m depth a 1.1 MeV alpha particle and a 1.1 MeV proton will both deposit all of their energy, the alpha particle in the first four microns and the proton over the entire path. In a given path length an alpha particle could deposit, at the most, four times the energy that a proton of that range would deposit. Figure 1 shows the energy deposited by various ions in 10 microns of silicon. The energy deposited scales nearly linearly with the depth considered. Nuclear reactions and scattering can also produce heavy ions that can cause upsets. From figure 1 we see that at 27 MeV Al ions can deposit much more energy than any alpha particle; however, in nuclear reactions or elastic scattering produced by 1-100 MeV protons or neutrons, ions such as Al will rarely have more than 1.5 MeV and therefore are important only for devices with low critical charge. We will see that there is one group of reactions producing heavy ions energetic enough to produce upsets in devices with a large critical charge.

Secondary radiation of the type that we are considering here does not normally have to be taken into account when examining circuit degradation due to radiation. The dose deposited by the secondary particles is a small fraction of the dose deposited by the primary particles, and the dose deposited by a flux of primary particles that will lead to soft errors is much smaller than the doses normally considered for circuit degradation and hard failures.

The cross section calculations reported here were done with the semi-empirical model used in the code TOWSTEP. This code predicts the peak cross section within +50%, the energy of the peak within 3 MeV, and indicates the general character of the cross section as a function of energy. The code has been checked primarily with proton induced reactions.

**Nuclear Reaction Cross Sections**

Figure 2 shows the predicted cross sections for isotopes which occur in typical semiconductor materials. Here we show the principal mode of particle emission leading to the final nucleus. We do not differentiate between (p,pn) and (p,d) reactions for example, but only show the resultant cross sections for producing the final nucleus.

**Alpha Production Cross Sections**

The alpha particles that contribute to the soft upsets come from several types of reactions. An examination of figure 2 shows that above 15 or 20 MeV relatively few alpha particles come from (n,α) or (p,α) reactions but instead most are produced in (n,αxn), (p,αxn), or (p,αp) reactions. One has to sum up the total number of alpha particles for all reactions to obtain the total alpha production cross section. Figure 3 shows some of the various calculated contributions to alpha production by nuclear reactions in silicon and the total alpha production. The total for proton induced reactions agrees with the experimental values obtained by Walton.

Figure 4 shows the total alpha production predicted in gallium, germanium, and arsenic. We see that germanium or gallium arsenide have total alpha production only slightly less than silicon. Figure 5 shows the total alpha production predicted in phosphorus, indium, and antimony. No material seems to have extremely low alpha production. The alpha particle energies will average in the vicinity of 9 MeV for Si and P, 12 MeV for Ga, Ge, and As, and 15 MeV for In and Sb, with corresponding average ranges of 60 to 90 m.

**Proton Production Cross Sections**

Figure 6 shows the calculated proton production cross sections. In this case we consider only the low energy protons with an evaporation spectrum, neglecting the high energy protons emitted in direct and pre-equilibrium reactions. In all cases the neglected component would add 200-300 mb to the cross sections. The proton energies will average in the vicinity of 6 MeV for Si and P, 7 MeV for Ga, Ge, and As, and 9 MeV for In and Sb, with corresponding ranges of 200 to 400 microns.

**Heavy ion production**

Nuclear reactions can also produce heavier, more ionizing particles. These can arise several ways: 1) elastic scattering, 2) reactions emitting several light particles, 3) reactions in which the breakup is directly
to heavy particles. Types 1) and 2) have large cross sections, but the energy of the recoiling heavy ion is ordinarily small. The maximum energy that can be passed to a nucleus in elastic scattering is \( E_x = \frac{(4m_1m_2)}{(m_1+m_2)^2} \), where \( E_x = 0.133 \) \( E_{\text{lab}} \) for protons or neutrons on silicon. At low proton energies there is an appreciable cross section for maximum transfer to the heavy nucleus. The cross section for maximum transfer decreases rapidly with increasing proton energy in such a way that the cross section for a given energy transfer is nearly independent of incident energy. A cross section of 10 mb/ster corresponds to \( \sim 1.7 \) MeV transfer at 14 MeV and \( \sim 1.2 \) MeV transfer at 100 MeV. The recoiling nucleus in types 2) and 3) has a maximum energy when the last steps of the reaction are evaporative, but even in these cases the conservation of momentum insures that the recoiling energy is small. In addition, type 3) reactions have small cross sections; totaling 30 mb for recoiling nuclei for n + 208Si reactions above 40 MeV. In heavier materials type 3) cross sections will be very small.

The heavy particles produced in type 4) reactions, in which the primary products are both heavy, can have enough energy to produce upsets. Table I presents our predictions of the cross sections for some of these reactions. These reactions will have effective thresholds in the region of 25-30 MeV and the peak values quoted will be in the vicinity of 50 MeV incident energy. These values might be low, as the present model does not include the direct knockout of heavy particles. The heavy particle predictions are slightly speculative and should be checked experimentally if effects due to these reactions are of importance in devices. Upsets due to heavy ions will be less important for the heavy semiconductors as the recoiling nuclei will have less energy, and the cross sections for type 4) reactions becomes very small.

**Calculation of Upset Rates**

The alpha production cross section can be used to calculate a volume production rate for alpha particles. The number of upsets is then obtained by multiplying this by the volume in which reactions may take place that produce the device volume a critical charge (Q_c) that will induce upsets. The alpha particles deposit the most energy in the device when they have long path lengths within the device and are near the end of their range. Therefore, if the critical charge is large, only a very small production volume contributes alpha particles with the appropriate energies and paths. Decreases in the critical charge of the device allow alpha particles over a wider range of energies to induce upsets, as can be seen from figure I.

There are standard methods of dealing with ionization paths that pass through a sensitive volume and for paths that originate inside a volume. In the alpha particle situation, the tracks start outside of the sensitive volume and end inside it, so these methods do not apply. As a rough approximation we assume that the reaction volume is the product of an assumed sensitive area of the chip times an effective depth \( D' \) for alpha production leading to upsets. This effective depth depends upon the critical charge but does not necessarily reflect physical device dimensions. We can consider two simple cases assuming an incident alpha particle with the range \( R \) of the average energy \( E_{\text{lab}} \). Assume a device of depth \( D \), a Q, that is large enough so that upsets are only produced when the particle stops in the sensitive volume with at least a path length \( D \) in that volume. This corresponds to the peak energy deposition in figure I. You then obtain an effective depth of \( D' = (R-D)/4R \).

If we consider \( n \) protons/cm² and a cross section of 200 mb, then the number of alpha particles produced in a cubic centimeter is 0.01N/cm³. Let us consider a 16k RAM and assume 20-micron cell size so that the area is \( (20\times10^{-4}) \) cm² x \( 1.6 \times 10^4 = 6.4 \times 10^{-2} \) cm². If we assume \( D' = 0.5 \) micron, appropriate for case 1, then upsets will appear at proton fluences of \( 0.3 \times 10^{18} \) p/cm², while if we assume \( D' = 30 \) microns, case 2, upsets will occur at \( 0.005 \times 10^{18} \) p/cm². These values are consistent with those observed by Guenzer et al.12. A more complete calculation would include the alpha spectrum and more details of the energy loss of the particle in the chip.

**Conclusions**

There are two important concepts when considering soft upsets produced by nuclear reactions. The total energy loss of the reaction products in the sensitive volume of the device is more important than the rate of energy loss. The nuclear reactions that lead to upsets occur in a small volume, whose size is more dependent on the critical charge than on the device dimensions, and which is mostly outside of the sensitive volume. The cross section calculations that we have presented help us to draw several conclusions about the occurrence of nuclear reactions leading to upsets:

1. Radiation fields of 10 - 70 MeV protons or neutrons will produce alpha particles in all semiconductors.
2. Alpha production does not change materially with semiconductor combinations.
3. If the critical charge drops by a factor of four below the critical charge for which alpha particles cause upsets, protons produced in nuclear reactions can also produce upsets.
4. In radiation fields above 30 MeV, ionization will be produced in silicon by reaction products heavier than alpha particles.
5. Some of the heavy reaction products will have energies such that they can cause upsets at critical charges for which alpha upsets do not occur.
6. Problems due to heavy reaction products can be greatly reduced by using semiconductors other than silicon or phosphorus.

**Acknowledgement**

I wish to thank Philip Shapiro for suggestions and discussions relating to this work.

**References**

8 A description of an earlier version of this code will be published in the proceedings of the "International Conference on Nuclear Cross Sections for Technology", Knoxville, Tennessee, October 1979.

Figure 1. Energy deposited in 10 \( \mu \)m of silicon by various ions. The scale on the left shows the energy deposited while the scales on the right show the number of electrons deposited. The straight part of the curves at low energy occurs when the ion range is less than 10 \( \mu \)m and it deposits all of its energy.
Figure 2. Calculated cross sections for neutron and proton reactions with various semiconductor materials. The curves show the cross section for production of a residual nucleus as a function of incident energy and are labeled with the principal mode of particle emission leading to that nucleus.

Figure 3. Calculated cross sections for total alpha particle production in silicon as a function of incident neutron and proton energy. The lower curves show the contributions of major reactions labeled with the emitted particles.
Figure 4. Calculated cross sections for total alpha particle production in the semiconductor materials gallium, germanium, and arsenic as a function of incident neutron and proton energy.

Figure 5. Calculated cross sections for total alpha particle production in the semiconductor materials phosphorus, indium, and antimony as a function of incident neutron and proton energy.
Figure 6. Calculated cross sections for the production of evaporation protons in various semiconductor materials as a function of incident neutron and proton energy.

Table I Heavy Particle Production

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