RAD Hard Radiation Effects and Environment

Semiconductors used in electronic systems are susceptible to damage by ionizing radiation. The purpose of the material on radiation issues in SD-18 is to introduce the reader to the basic concepts of how various forms of radiation degrade semiconductor performance, the radiation environments that systems are typically exposed to, and the evaluation methods used to assure that a component will survive its specified radiation environments. In general, this guide will focus on the issues at the electronic component level, not the complex issues of system design for a radiation environment.

Basic Concepts

The source of radiation is either a particle or a photon. Particles include alpha particles (helium nuclei), beta particles (electrons), protons and neutrons. Photons are either x-rays or gamma rays, with the difference being the source of the photon, where gamma rays are defined as the result of a nuclear process, while x-rays are extra-nuclear. Particles may or may not carry an electrical charge, and have mass, while photons carry no charge or mass. To first order, the energy of the particles is kinetic ($\frac{1}{2}mv^2$) while the energy of the photon is $h\nu$, where h is Planck's constant and ν is the frequency of the photon. The two primary interactions of radiation with electronic components are ionization and displacement.

In ionization, a electron is ejected from an atom due to the collision, by one of three processes. The photoelectric process dominates at low energy. In the photoelectric process, a photon is absorbed completely in a collision with an electron, and the electron is ejected from the atom. This can happen whenever the energy of the photon is greater than the binding energy of the electron. The kinetic energy of the freed electron is given by $T = h\nu - B$, where $h\nu$ is the photon energy, and B is the binding energy of the electron. For silicon, the binding energy of an electron is 3.2 eV. Compton scattering and pair-production are the other mechanisms, and are described in references [xx]. In semiconductors, ionization creates a trail of free electron-hole pairs that did not exist before the radiation event. While some fraction recombine quickly, many are either (a) swept away by the existing field (behaving like a short-duration current source at the circuit node), (b) trapped in non-conducting oxides or (c) drift within the semiconductor, where it either recombines eventually, or is rendered immobile by an interface trap. If the mobile charges large, then these photo-currents directly upset or damage the transistors, as high current densities are obtained, a phenomena called dose rate upset or burnout. When the photo-current is generated by a single energetic particle, and only effects one circuit node, this is considered a single event upset or burnout. While the photo-currents are a transient event, their residual effects can be permanent. When the mobile charges are trapped in the semiconductor, the effects of the trapped charge modify the expected characteristics of the transistor (e.g., a N-channel MOSFET is biased on by trapped holes) and thus degrade the performance of the circuit with total dose effects. While trapped charge can and does anneal over time and thermal cycling, to first order it can be considered as permanent damage.

Displacement damage occurs when a particle impacts the nucleus with sufficient energy to remove or displace it from its location in a crystal lattice. The classic example is neutron damage. Neutrons are uncharged particles and hence can penetrate the electron cloud of an atom and interact with the nucleus. With sufficient energy, this elastic scattering displaces the nucleus from its lattice location, and causes most of the electrical, chemical and physical changes observed. Since this is a degradation of the bulk characteristics of the silicon, bulk effects, such as the gain of a bipolar transistor or the resistance of a diffused resistor, are affected first by displacement damage. Displacement damage is also considered to be permanent damage.

Radiation Environments

There are three primary radiation environments of concern to electronic components. First are nuclear weapon effects. While primarily a concern for military systems, some effects such as electromagnetic pulse (EMP) are so widespread that commercial infrastructure has concerns as well. The second environment is outer space, primarily the natural environment, which can be quite harsh in certain orbits, but also the enhanced radiation environment if nuclear weapons are detonated in space. Finally, nuclear reactors and certain high energy accelerators create a radiation environment that requires care in implementing electronic systems. For the purposes of this introduction, reactors include not only nuclear power stations, but also experimental reactors, high energy physics experiments and medical instruments used in most hospitals as well.

The classic military concern since WWII has been the effects of nuclear weapons. When a nuclear weapon is detonated in the atmosphere (endo-atmospheric) a large burst of fission X-rays and gamma rays and fission and fusion neutrons are generated. While a fraction of this energy survives to directly impact the exposed system, much of the emitted radiation reacts with the surrounding atmosphere to produce a broad spectrum of X-rays, gamma rays and energetic particles and thermal energy. These prompt effects occur within milliseconds of the burst (depending on distance from the burst), delayed radiation, consisting of fission-product neutrons and gamma rays, and activation gamma rays occur at a relatively high rate for the first minute. Finally, residual radiation from fallout, consisting of several sources of gamma rays, lasts for years and can accumulate a significant dose over time. If the weapon is detonated outside the atmosphere (exo-atmospheric), the results are quite different. Since there is little or no atmosphere to interact with the radiation, there is no attenuation of the initial x-ray, gamma ray and neutron yield, except as a function of distance from the burst ($1/R^2$). The activated debris field expands radially from the burst. Emitted electrons and protons are captured by the earth's magnetic field lines and held for long periods of time (pumping the belts), creating a high dose environment for a long period of time. The effects of the Starfish atmospheric test were detectable for several years after the 1962 test, destroying several satellites in the process.

The natural space environment is a concern for all satellites. There are three primary sources: electrons and protons trapped in the van Allen radiation belts, the solar proton flux (varies with the 11-year sunspot cycle), and galactic cosmic rays. The trapped radiation is highly dependent on altitude and latitude. Low earth orbit (LEO) (less than about 480 km) is where manned missions including the shuttle and ISS occur, and are mostly below the belts. This is the most benign environment. From about 500 km to 6,000 km are the proton belts, which are hard to shield and significantly damaging, making certain orbits such as mid-earth orbits (e.g., half geo-synchronous) a harsh environment. The electron belts extend from about 6,000 km to 60,000 km, and while easier to shield than protons, still create significant system problems. The more energetic electrons cause accumulated dose problems as well. Latitude causes problems due to the shape of the earth's magnetic field. Since the field lines flow from north pole to south pole, and are toroidal in shape, maximum protection is found near the equator, and minimal near the poles. Thus, the inclination of the satellite’s orbit also has a bearing on the average dose rate. In addition, many satellites fly in elliptical orbits, thus the dose rate varies considerably during the orbit. The solar proton flux is protons released from the sun as part of the fusion process. While there is a constant flux, during solar storms (sunspots) this flux can increase by orders of magnitude, affecting even LEO satellites. The pressure of this flux modifies the shape of the magnetosphere, further enhancing dose. Finally galactic cosmic rays are very energetic ions of all elements (though there is a dramatic falloff in number above iron) that originate from outside the solar system. These energetic ions primarily cause single event effects wherein the function of a circuit is modified by a single particle passing through a sensitive volume (e.g., a digital latch switches state). More permanent effects such as latch-up and burn-out are also possible.

Nuclear power systems primarily emit neutrons, which activate surrounding materials, creating gamma rays. To the extent possible, sensitive systems are protected by massive shields, but some elements must be in substantial radiation fields. High energy physics accelerators often have harsh radiation environments in various areas. For example, the Large Hadron Collider currently under construction at CERN in Switzerland will subject the experiments to massive doses of both atomic and sub-atomic particles, over an extended period of time. The electronics required in the experimental area must withstand very high radiation levels.