Chapter 10. Radiation Effects in MMIC Devices

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I. Introduction

The use of microelectronic devices in both civilian and military spacecraft requires that these devices preserve their functionality in the hostile space environment throughout the mission life. An important feature of this environment is the presence of radiation of various types, including that from man-made sources. Unlike other aspects of reliability discussed in this chapter, radiation is unique and is not a requirement for nearly all other high-reliability applications, such as automotive, medical and terrestrial communications. Thus, because of the distinctive nature of the radiation environment, it is important to understand the effects of radiation on microelectronic devices and circuits, in particular on MMIC devices, used in space systems.

In this chapter we present a summary of the current understanding of the effects of radiation on MMIC devices. We begin with very brief background discussions of the radiation environment, and of the more “classical” microelectronic radiation effects found in Si-based devices, especially digital CMOS. As we pursue our discussion of radiation effects in MMIC devices, we will also briefly contrast these effects with those in other III–V-based technologies such as GaAs digital and III–V photonic devices.

II. Radiation Environments and Sources

Because this guideline is intended primarily for space applications, our focus in this discussion will be on the natural space-radiation environment. However, it is important to remember that there are other important sources of radiation. For example, many military space assets must be designed to maintain functionality in the presence of an environment that is enhanced by nuclear weapons. This enhanced environment has been discussed in detail recently by Messenger and Ash [1]. In addition, there are other specialized applications that may include narrowly defined radiation requirements, such as nuclear power stations, nuclear waste disposal site monitors, high-altitude avionics, and medical radiation treatments. We conclude this section with a brief discussion of the effectiveness of radiation shielding.

A. The Natural Space Radiation Environment

The radiation environment in space depends strongly on location, and is composed of a variety of particles with widely varying energies and states of ionization. Thus, radiation requirements are driven in large part by the nature and trajectory of the mission. For Earth-orbiting systems, such as communications satellites, the primary sources of radiation are electrons and protons trapped by the Earth’s magnetosphere, as shown in the highly simplified diagram in Figure 10-1. These regions of trapped electrons and protons, called the Van Allen belts and discovered in 1958 by Explorer 1, are significant between the altitudes of approximately 1000 km and 32,000 km. Their extent is greater than this, but the particle flux levels drop rapidly outside this altitude range. As indicated in Figure 10-1, the altitude distributions of electrons and protons are significantly different. The distribution of electrons, whose energies reach a maximum of about 7 MeV, shows two altitude peaks at about 4000 km and 24,000 km, giving rise to

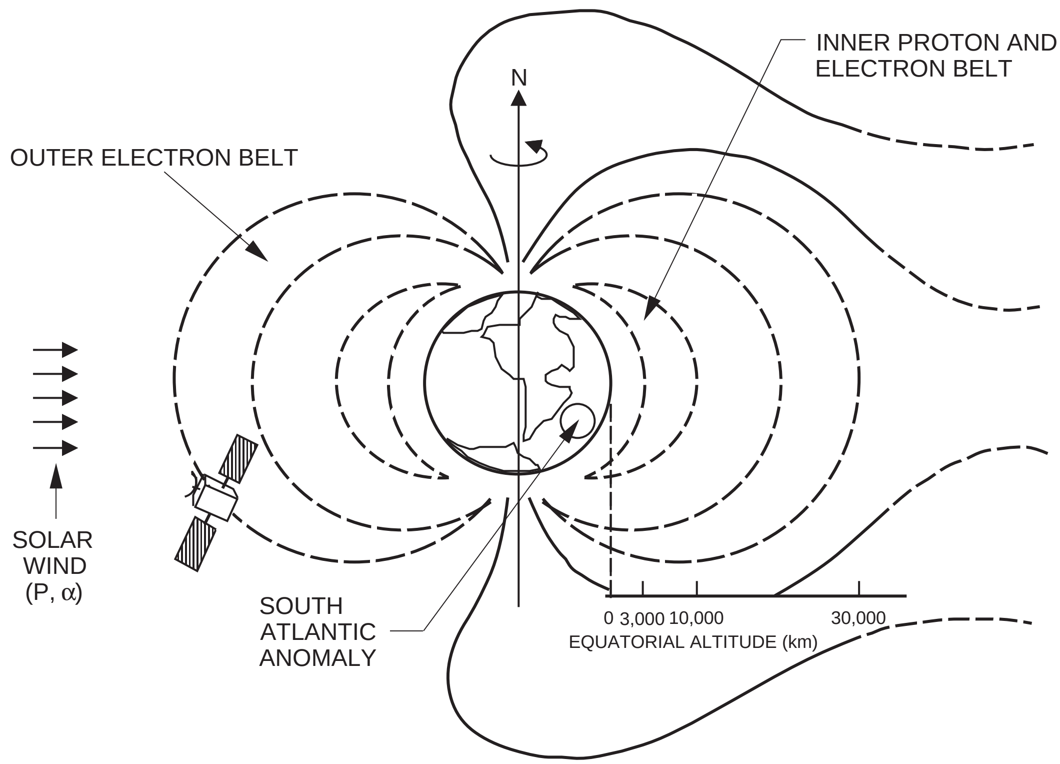

Figure 10-1. Schematic diagram of the Earth's Van Allen radiation belts formed by the Earth's magnetosphere.

the two belts shown in Figure 10-1 with a relatively unpopulated "slot" between the inner and outer electron belts. Protons are restricted to the inner belt, but their energies can be much higher than those of electrons—in excess of several hundred MeV. For both electrons and protons, the higher energy particles are concentrated at lower altitudes. At the lower energies, particle fluxes can exceed 1×10^8 electrons or protons per cm^2 per day.

Although the simple diagram in Figure 10-1 suggests that the belts are relatively symmetric, there are important exceptions to this overall symmetry. For example, at the Earth's poles, the outer electron belt extends downward to much lower altitudes. These "horns" in the belts cause a strong dependence of the particle flux at a given altitude on the angle of inclination. Another very important distortion is caused by the fact that the dipole axis of the Earth's geomagnetic field is offset from the Earth's axis of rotation by about 11 deg and is displaced by 500 km toward the Western Pacific. The result is that, off the coast of Brazil, the Van Allen belts reach down into the upper part of the atmosphere so that satellites at low Earth orbit (LEO) receive significant exposure to radiation over this region, called the South Atlantic Anomaly (SAA). Finally, the Sun also has a strong effect on the shape of the Earth's magnetosphere. The solar wind causes a "bow wave" and a "wake" in the antisolar direction that is similar to a boat moving through water and results in the extension of the magnetosphere to much greater distances from the Earth, as indicated schematically in Figure 10-1.

The characteristics of the Van Allen belts briefly summarized above result in dose-rate distributions for electrons like those shown in Figure 10-2 for an altitude of

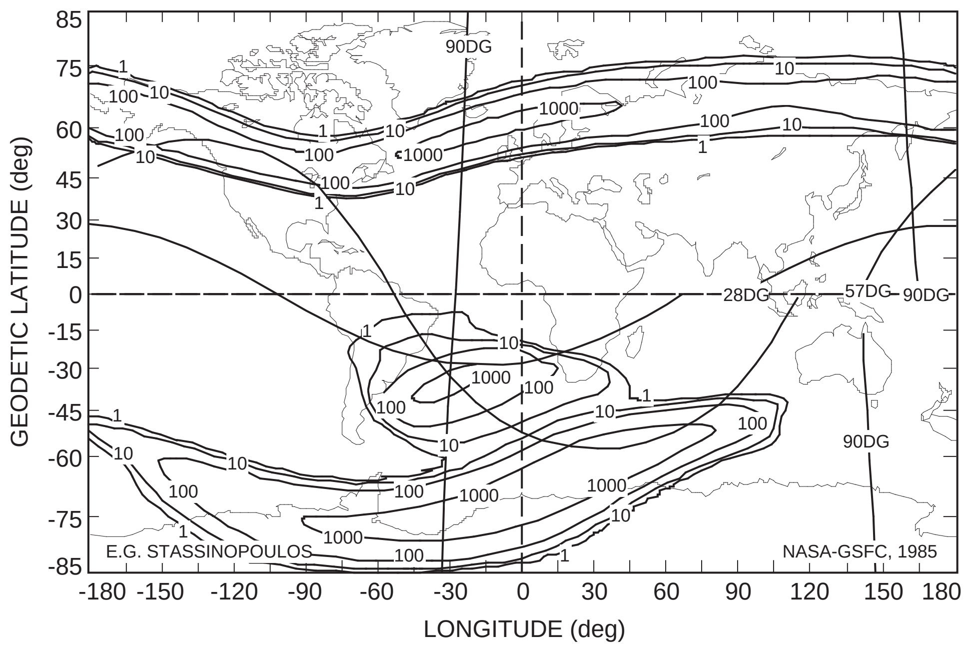

Figure 10-2. World map contours of electron dose at an altitude of 500 km. For the contours, 100 is equal to approximately 8.6 rads(Si) per day. (From [3]; ©1994 IEEE.)

500 km behind a spherical shield with thickness of 0.2 gm/cm^2 (equal to approximately 30 mils for Al) [2,3]. The dose rate is given in rads(Si) per unit time, where a rad is a measure of absorbed ionizing energy and is equal to 100 ergs/gm of the absorbing material (Si in this case). Note the clear delineation of the SAA by the isodose-rate curves, and that the dose rate is greater near the poles. Note also that the low inclination angle orbits do not pass through the higher dose-rate zones near the poles. It is important to emphasize that these dose rates are behind an Al shield because of the presence of very high fluxes of low energy (< 0.1 MeV) electrons and protons that can drive the dose to much larger values when no shielding is present.

Solar flares are another important source of ionizing radiation particles, particularly protons. Electrons, alpha particles, and heavier ions are also emitted, but at much lower fluxes than the high energy protons. The first indication that a solar flare has occurred is the arrival near Earth of a burst of X-rays. After about 10 min, highly energetic protons begin to arrive and significant fluxes of protons can last for a few hours to a day or so. As shown in Figure 10-3, the general sunspot activity follows an approximate 11-year cycle, although not all of this sunspot activity results in significant solar flares. Note that large flare occurrences are concentrated during solar max periods. The very large flare that occurred in August 1972 has become a benchmark against which conservative estimates of solar flare proton fluxes are made. As indicated in Figure 10-3 by the energy partition, solar flares can vary significantly in their proton energy spectrum, with some exhibiting much harder spectra than others. The inability to predict when a solar flare will occur and what its particle and energy content will be forces space system designers to use conservatively large estimates of potential flare activity.

The interaction of particles ejected by the Sun with the Earth's magnetosphere results in complex and sometimes unexpected dynamic behavior of the radiation flux [3].

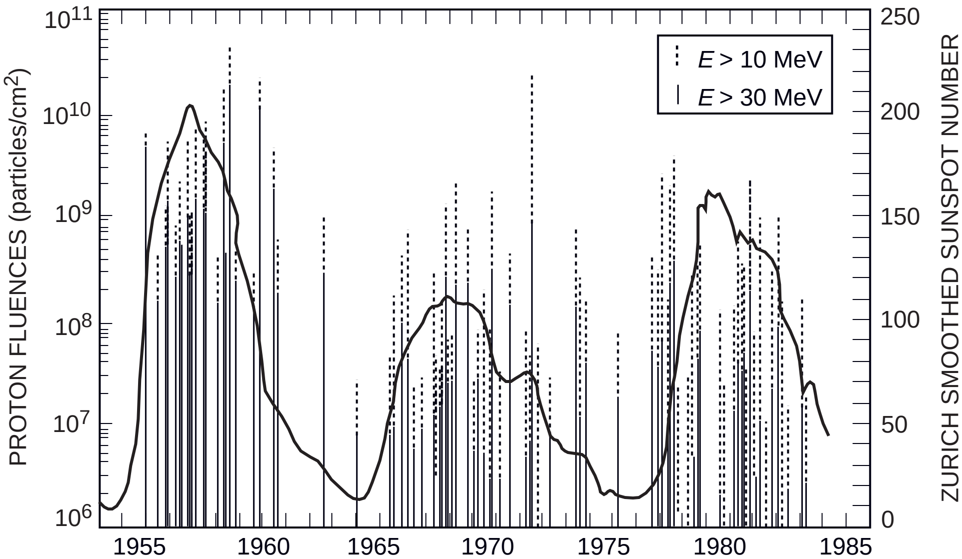

Figure 10-3. Sunspot activity and solar flare events for solar cycles 19, 20, and 21. Note the very large flare in 1972 that was a benchmark event. (From [4]; ©J. Geophys. Res., 1988.)

For example, one might expect that radiation fluxes would in general be greater around periods of solar max as implied by Figure 10-3. However, at low altitudes, the proton fluxes are lower at solar max because of an increase in the density of the atmosphere at altitudes of 200 to 1000 km; the greater density is caused by increased solar energy output at solar max. This density increase results in a depletion of those trapped particles that approach minimum altitudes in the belts. At the higher altitudes of geosynchronous orbits (GEOs), for example, complex dynamic fluctuations are also observed because of the influence of the Sun on the magnetosphere's properties. We also note that for low altitudes and angles of inclination, the magnetosphere provides a shielding effect on solar particles, but that for polar orbits, the flare protons can be funneled down to low altitudes, again emphasizing the dependence of radiation exposure on the angle of inclination for orbiting satellites.

The third important source of radiation in the natural space environment is galactic cosmic rays (GCRs), consisting of about 85% protons, approximately 14% alpha particles, and about 1% heavy nuclei [3]. These particles originate outside the solar system and are believed to be distributed uniformly throughout the galaxy. GCRs can be very energetic, reaching energies as high as 10 GeV/nucleon. While ions as heavy as uranium have been observed, the incidence of ions with atomic numbers greater than iron is rare. The distribution of GCR ions as a function of energy is shown in Figure 10-4. The heavier ions like Fe are present in much smaller densities. However, because the heavy ions deposit so much energy as they pass through a semiconductor device circuit, they can be more damaging overall even though they are much rarer in occurrence.

The energy and spatial distributions of GCR particles vary with location of the spacecraft. For interplanetary missions, typical of NASA projects, the energy spectrum is undegraded and the GCR flux is omnidirectional. However, for low-inclination-angle LEO satellites, the Earth's magnetosphere provides partial shielding of the GCR flux. This effect is shown in Figure 10-5 for Si ions as a function of their energy and the angle of orbit inclination at an altitude of 600 km [3,5]. Note that at small angles, the low-energy portion of the spectrum is strongly attenuated, while at large polar angles

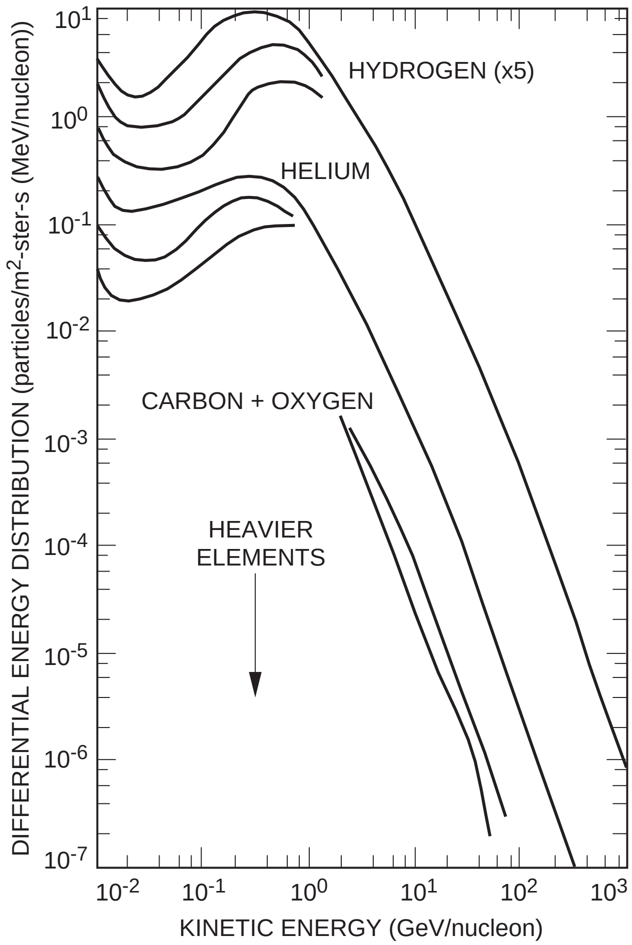

Figure 10-4. Distribution in energy and abundance of various galactic cosmic ray particles. (From [5]; ©1988 IEEE.)

(90 deg), there is a much smaller reduction in the flux of Si ions due to shielding by the magnetosphere.

While there is some uncertainty in calculating the expected radiation environment for a particular mission, primarily because of solar flares, sophisticated models and calculational codes have been in place for some time, and these are more or less continuously improved upon and updated [5–8]. Thus, it has become fairly standard practice to calculate environmental predictions of expected dose and heavy ion flux for given missions. The same is true for shielding calculations, which also can be quite complex for a relatively complicated spacecraft structure.

B. Other Radiation Sources

Military space assets are often designed to withstand not only the natural space environment, but also the added components due to detonation of nearby nuclear weapons. For this scenario, in addition to GCR ions, solar flare particles, and the Van

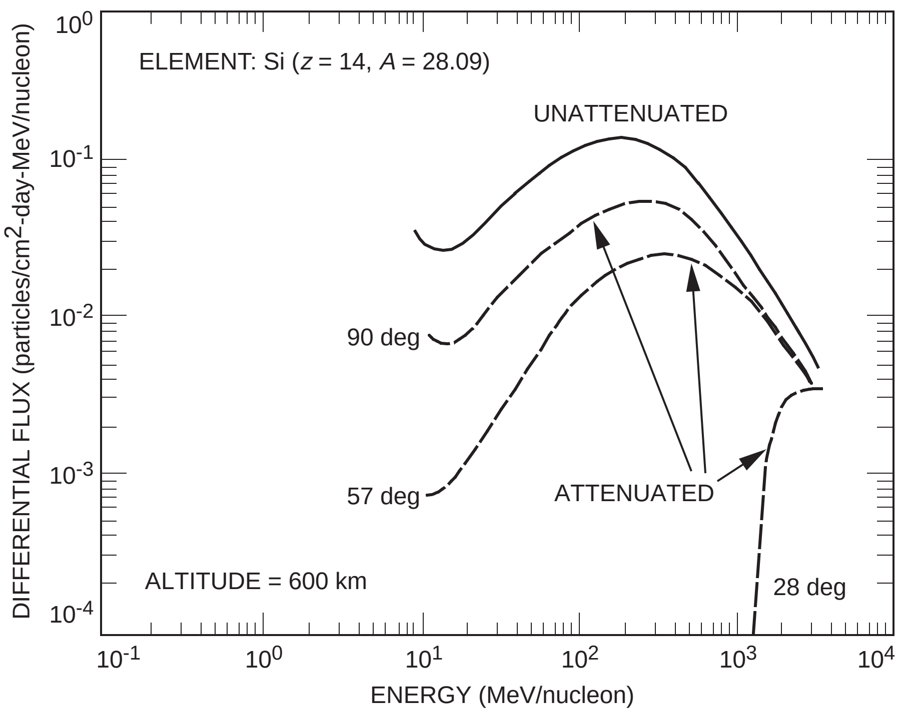

Figure 10-5. Attenuation of galactic cosmic ray Si ions by the Earth's magnetosphere at an altitude of 600 km for various angles of inclination. (From [5]; ©1988 IEEE.)

Allen belt electrons and protons, one must add large fluxes of neutrons, high-energy gamma rays and electrons, low-energy X-rays, and prompt bursts of gamma rays at very high dose rates. Thus, the military radiation environment is very difficult and demanding, particularly the prompt gamma dose, which is typically in the range 10^9 rad(Si)/s to 10^{12} rad(Si)/s.

In specialized cases, other man-made sources of radiation can be important. For interplanetary missions that extend to large distances from the Sun, as for the Galileo mission to Jupiter, nuclear sources are often used to provide electrical power to the spacecraft and its instruments. Radioisotopic thermoelectric generators (RTGs) generate enough gamma rays and neutrons to affect the performance of microelectronic circuits on the spacecraft near the RTGs. In the future, if other nuclear power sources, such as spaceborne nuclear reactors, come into being, there will be similar concerns for the exposure of electronics located near the nuclear power source.

When high-energy radiation passes through a material such as a radiation shield, nuclear interactions occur with nuclei of the material resulting in the emission of secondary radiation in the form of a continuous energy spectrum of energetic photons (Bremsstrahlung), gamma rays, electrons, alpha particles, and neutrons. These secondary particles can also cause damage to electronic circuits in the same manner as the primary radiation. Thus, in determining the total radiation flux that reaches the microelectronic devices and circuits, secondary radiation must be taken into account, especially if thick, high-Z (high atomic number) materials are present.

C. Radiation Shielding

The effectiveness of radiation shielding as a method of protecting electronics is often dependent on the circuit and its packaging or board configuration. However, some general comments concerning shielding are appropriate at this point. We have already noted that the various sources of radiation in the natural space environment contain significant low-energy components. Thus, even a nominal shield (less than 100-mil Al), as typically provided by the spacecraft structure and electronics boxes, can reduce the dose by several orders of magnitude. This effect is easily seen in Figure 10-6, which shows differential trapped proton flux as a function of energy and Al shield thickness for an orbit at 500 km altitude and an angle of inclination of 60 deg [5]. Very often, one of the difficulties in defining a total-dose radiation requirement with any precision for a specific mission results from variations in shielding with location in the spacecraft. Usually a nominal total dose—for example, 100 krad(Si) for the Cassini mission—is defined by the expected mission trajectory and the environment encountered; specific doses are then calculated for particular positions within the spacecraft. The impetus for following this procedure is especially strong when designers wish to use parts that do not meet the nominal requirement.

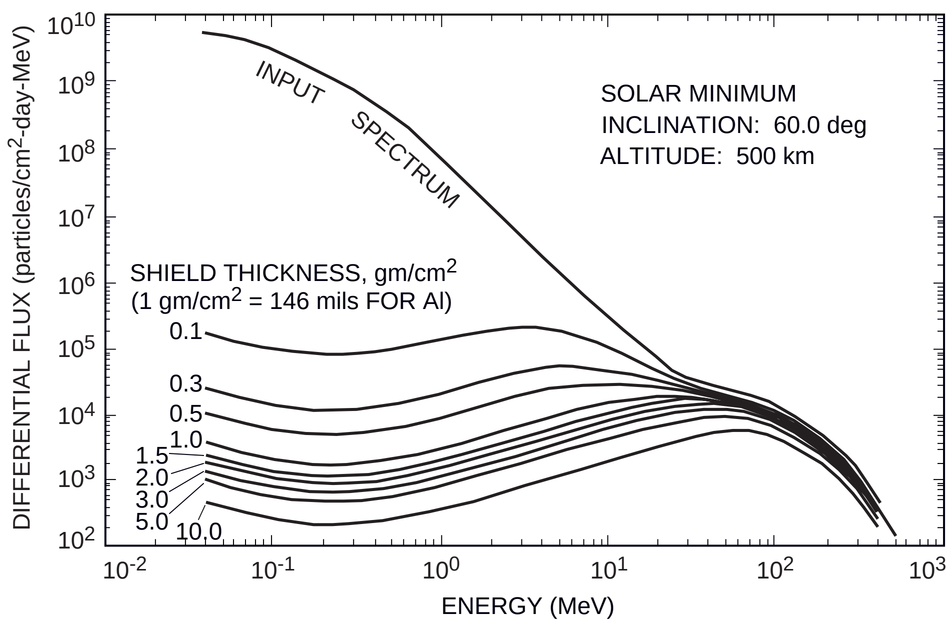

Figure 10-6. Van Allen belt trapped proton spectra emerging from spherical shields of various thicknesses for a 500-km orbit at 60-deg inclination and solar minimum. (From [5]; ©1988 IEEE.)

With greater use of commercial electronic parts in space, there are often cases when the shielding provided by the spacecraft structure is insufficient, and alternative radiation-resistant parts are not available. In such cases, spot shielding of the part is appropriate, including integrating shield material (high-Z elements like tantalum or tungsten) into the part package itself, a technique often referred to as "RadPak." As noted above, the implementation of these various shielding schemes to reduce the expected total dose is aided by the fact that shielding calculations used to determine the effect of a material on the flux and energy spectra of various types of radiation are well established. These calculations also take into account the production of secondary radiation.

While shielding can facilitate the use of "soft" parts in many cases, it is important to realize that shielding is not always effective, and can even make the situation worse. As a rule of thumb, shielding is most effective in reducing the low to moderate energy component of ionizing radiation, that is, electrons and protons. For very-high-energy radiation, such as gamma rays and GCR ions, shielding is not particularly effective, and can even be detrimental. This is partly due to the production of secondary radiation in the shield material, and also because the energy loss per unit length in the electronic part can increase with decreasing particle energy. The production of secondary radiation results in the asymptotic behavior of shielding effectiveness. In other words, the first thin layer is much more effective in reducing radiation than the additional thicknesses of shielding, as shown in Figure 10-6. Thus, beyond a few tens of mils of Al-equivalent shielding, the weight penalty is often more important than the added benefit of the radiation shielding.

The effectiveness of shielding in reducing the overall amount of radiation impinging on spacecraft electronics causes a sharp distinction between the natural space environment and the nuclear weapon-enhanced environment [1]. As noted earlier, weapon detonation results in a burst of prompt, high-energy gamma rays and, somewhat later in time, a significant fluence of 14-MeV neutrons. Shielding is of little use in moderating either of these radiation threats. Similarly, it is difficult to shield against the neutrons and high-energy gamma rays continuously emitted by RTGs as a byproduct of the power generation process. For this reason, the RTGs on Cassini have proven to be a challenging radiation threat to nearby microelectronics on the spacecraft.

III. Radiation Effects in Semiconductor Devices

In this section, we very briefly review the salient features of the effects of radiation on semiconductor devices. More thorough discussions can be found in References [1,9–11], and in the yearly Short Courses on this topic presented and published by the IEEE Nuclear and Space Radiation Effects Conference. To introduce this subject, we focus on radiation effects in Si devices, particularly digital complementary metal-oxide semiconductor (CMOS) and analog bipolar. In addition to allowing us to briefly review traditional radiation effects, this focus will provide a baseline for our review of radiation effects in MMIC devices. For purposes of discussion, we designate three categories of radiation effects: (1) ionizing radiation effects, (2) displacement damage effects, and (3) single-particle or single-event effects (SEE).

A. Ionizing Radiation Effects

With the exception of neutrons, the various types of radiation making up the natural and weapon-enhanced environment—X-rays, gamma rays, electrons, protons, alpha particles and heavier ions—all deposit significant amounts of ionizing energy in semiconductor devices. In semiconductors and insulators, the absorbed ionizing energy manifests itself as electron-hole pairs that can separate, migrate through the material, and become trapped at certain locations, often resulting in an alteration of the properties of the device in which the energy was deposited. The fraction of the total generated charge, electrons and holes, that eventually becomes trapped is called the charge yield and depends on the structure and operating conditions of the device during radiation exposure, and also on the type of radiation and its energy. In many cases, nearly all the charge recombines or is collected at contacts in such a way that the ionizing radiation has