Radiation handbook for electronics

A compendium of radiation effects topics for space, industrial and terrestrial applications

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Robert Baumann

Early in his 29 year career at TI, Robert Baumann discovered that the reaction of $^{10}$B with low-energy cosmic neutrons was a dominant reliability risk in digital electronics and developed mitigation schemes that reduced product failure rates nearly ten-fold. From 1993-1998, He was involved in transistor and radiation effects reliability and advanced failure analysis at TI's Mihomura Fab and Tsukuba R&D Center in Japan. When he returned to Dallas he led radiation effects programs for the advanced technology reliability group. He co-led the SIA's expert panel, which successfully negotiated with the U.S. Government to change ITAR export control laws that posed a serious risk of export restriction to advanced commercial technologies. Baumann was one of the primary authors of the JEDEC (JESD89, 89A) industry standard for radiation characterization in the terrestrial environment for which he was awarded the JEDEC Chairman’s Award. In 2012 he moved to the high reliability product group focused on improving the characterization, modeling and reporting of radiation effects. Baumann was elected TI and IEEE Fellow. He has coauthored and presented more than 90 papers and presentations, two book chapters and has fifteen U.S. patents. Baumann retired from TI in 2018.

Kirby Kruckmeyer

Kirby Kruckmeyer started his career at National Semiconductor (acquired by Texas Instruments in 2011) as a process engineer, developing processes for the world’s first 5-inch analog wafer fab. During this time, Kruckmeyer gained experience with semiconductor physics, passivation charging effects and radiation-hardened processing. From 1990-1992, Kruckmeyer was an assignee from National Semiconductor to Semiconductor Manufacturing Technology (SEMATECH), an industry consortium established to improve processing technology in the United States. There, he supervised engineers from other companies in the development of 150-mm process technologies. After finishing his assignment, Kruckmeyer returned to National, where he moved into product development and eventually was the product line manager for National’s Automotive Systems group. In 2005, Kruckmeyer moved in the High Reliability product group. He was instrumental in developing National Semiconductor’s leadership in space-grade data converters, enhanced low dose rate sensitivity-free products and radiation testing. At Texas Instruments, Kruckmeyer continues to support space applications, radiation testing and space product development. He has authored and presented over 20 papers, sits on radiation testing standards committees, and participates in radiation conferences.
Texas Instruments has one of the longest space-flight histories of any semiconductor vendor. Even before Texas Instruments engineer Jack Kilby conceived and built the first integrated circuit (IC) in September 1958, Texas Instruments transistors had flown into space on the U.S.’s first satellite, Explorer 1, which launched on Jan. 31 that same year.

Since then, products from Texas Instruments have flown on many space missions. Notable and historic missions with Texas Instruments products on board include:

- Telstar 1, the first broadcast TV satellite
- Apollo 11, marking the first man on the moon
- Mariner 2, the first successful interplanetary spacecraft
- Voyager 1, still traveling after 40 years and now the farthest human-made object from Earth
- Every Space Shuttle mission from 1981-2011
- Navigational satellites supporting GPS and the Global Navigation Satellite System (GLONASS)
- The Hubble space telescope
- The International Space Station
- Rosetta and Philae, the European Space Agency comet orbiter and lander, respectively
- The Mars Rover
- Mangalyaan, the Indian Space Research Organization Mars orbiter
- KickSat, a group of 104 microsatellites launched on a single rocket into low Earth orbit in 2014

Former Texas Instruments researcher Mary Ellen Weber served as an astronaut on Discovery Space Shuttle mission space transportation system (STS)-70.

Numerous commercial, scientific and governmental satellites using Texas Instruments products have launched since 1958 and continue to launch weekly.

Through its acquisitions of Unitrode in 1999 and National Semiconductor in 2011, Texas Instruments added significant product breadth, expertise and technology to its internal space-grade semiconductor capabilities. Building on this long heritage in space flight, Texas Instruments continues to innovate and bring new products to the space ecosystem. Texas Instruments offers one of the industry’s broadest portfolios of ICs for space applications, covering a wide range of device types. Power management, data converters, amplifiers, clocks and timing, interface, processors, and sensors are just a few of the device types Texas Instruments provides for space electronics systems. Texas Instruments’ portfolio includes both Class-V qualified manufacturer list (QML) and radiation-hardness assured (RHA) ICs, demonstrating the company’s long-standing commitment to the space electronics market.
Chapter 1: Radiation environments

The type and magnitude of radiation effects observed in electronics are largely defined by specific device properties and the radiation environment in which the devices are used. In this chapter, we review three of the primary radiation environments: the natural space environment encountered outside the protective shielding of the Earth’s atmosphere; the natural terrestrial radiation environment in which most electronic applications operate; and the specialized man-made radiation environments encountered in some medical, industrial and military applications. In later chapters, we will deal with the different radiation effects and how they manifest in different device types.

1.1 The space radiation environment

Three sources of radiation define the space environment in our solar system:

- Galactic cosmic rays (GCRs), a nearly isotropic flux (same in all directions) predominantly comprising extremely energetic protons impacting the Earth from outside our solar system.
- Solar radiation, comprising a stream of lower-energy photons, plasma and magnetic flux that the sun emits continuously in all directions, like an ever-present “wind” of particles. This solar wind is punctuated by sporadic emissions from solar storms. Solar flares and coronal mass ejections (CMEs) generate localized intense particle bursts with much higher energies and fluxes than the steady-state solar wind.
- Radiation belts, accumulations of energetic particles diverted and trapped into toroidal-shaped regions around planets in response to their magnetic fields.

The reliability of microelectronic components in the harsh space radiation environment is characterized by the accumulation of ionizing and displacement damage dose (DDD), as well as a high rate of single-event effects (SEEs). The radiation exposure that on-board electronics receive is a function of the orbit that the spacecraft follows, the mission duration, the amount of shielding, and the number and magnitude of solar flares or CMEs that might have also occurred during the mission.[1-3]

The Earth's magnetic field has a varying effect on shielding space radiation, depending on the mission orbit.[4] Figure 1-1 shows the different orbit types and their properties. Leaving the Earth’s surface, Figure 1-1 shows the low Earth orbit (LEO), a geocentric orbit with an altitude ranging from 0 to 2,000 km (1,240 miles). In order to keep a satellite in orbit with minimum energy, it is crucial to eliminate atmospheric drag, so practical Earth orbits begin at approximately 167 km (100 miles), and have an orbital period between one and two hours.

![Figure 1-1. Illustration of orbit types, shapes and properties.](image-url)
LEOs are relatively low-altitude orbits and thus the least expensive in terms of energy expended to achieve orbit. Because of this, round-trip signal distances are the shortest; signal communication delays are minimal, and surface details are better resolved than for higher orbits. The orbital periods of LEO satellites range from approximately 1 1/2 hours to a bit more than two hours.

Medium Earth orbit (MEO) is defined between LEO and geostationary orbit (GEO) at 35,786 km (22,236 miles). MEO is usually used for navigation (GPS), communication and science observation missions. The orbital periods of MEO satellites range from approximately two to nearly 24 hours.

Geosynchronous orbit (GSO) and GEO both match the Earth’s rotation, and thus complete one full orbit every 24 hours. A satellite in GSO stays exactly above the equator, while a satellite in GEO will swing north to south during its orbit. Any orbiting spacecraft with an altitude above GEO is considered to be in high Earth orbit (HEO). HEOs are orbits usually reserved for missions that need to get away from the heavy electromagnetic traffic present in lower orbits, such as those focused on monitoring deep space.

LEO – particularly equatorial orbits, where the magnetic shielding effect is maximized – provides the greatest benefit in terms of minimizing radiation effects. At higher altitudes, orbits such as MEO or GEO, and/or highly inclined orbits or polar orbits, the shielding provided by the Earth’s magnetic field is significantly reduced, leading to higher particle fluxes and a higher probability of more disruptive events. Higher fluxes and higher-energy particles will expose missions with high inclinations or polar orbits, since the Earth’s magnetic shielding becomes less effective at higher/lower latitudes away from the equator. For interplanetary flights far from the Earth’s protective magnetic field, the spacecraft is exposed to the high fluxes of energetic particles.

**Galactic cosmic rays**

Before focusing on the local space environment of our solar system, consider the environment on a bigger scale. “Outer space” is often portrayed as a complete absence of material (empty space), but in actuality, even the vast seemingly empty spaces between the stars are filled with matter and energy. The material that occupies the space between the stars, called the interstellar medium, mostly consists of hydrogen, with a smaller fraction of helium and trace amounts of heavier elements, plus a smattering of dust. The interstellar medium is not a perfect vacuum, but has an extremely low density from $10^4$ to $10^7$ atoms/cm$^3$. In stark contrast, our atmosphere has a density of $\sim 10^{19}$ atoms/cm$^3$.

The interstellar gas usually forms large “clouds” of neutral atoms or molecules. Near stars or other energetic bodies plus the dilute gas clouds become ionized. The gas in the interstellar medium is not static but moving, compressing or dissipating in response to the local interplay of magnetic, thermodynamic, gravitational and radiation processes. This turbulence drives the dynamic evolution of the interstellar gas, slowing or halting collapse over larger ranges while initiating local compression and star formation at more localized smaller ranges. Interstellar gas is both the substrate and the source of galaxies and stars.

The interplanetary medium of our solar system begins where the interstellar medium ends. The solar wind, or flux of energetic particles emitted continuously and spreading radially away from the sun, eventually slows down to subsonic velocities at a distance about twice the distance of Pluto’s orbit in a region known as the termination shock. In this region, the solar wind density is so low that it is effectively impeded by the “force” of the interstellar medium. The heliopause is the outer extent of the sun’s magnetic field and solar wind. Within the heliopause is the heliosphere, a spherical bubble that encompasses the sun and planets. The heliosphere acts as a giant electromagnetic shield, protecting the planets from some of the incident GCR flux. Cosmic-ray particles with less than $\sim 50$ MeV of kinetic energy are unable to penetrate within the heliosphere due to the energy of the solar wind within this volume, such that nearly 75% of the incoming GCR particles are stopped.

*Figure 1-2.* The heliopause represents the boundary where the sun’s influence ends. The heliosphere is the volume defined by the boundary where solar wind velocity ceases being supersonic (termination shock) and is no longer able to filter out the interstellar medium.  

Scientists believe that GCRs accelerate due to high kinetic energies caused by shock waves from supernova explosions propagating in the interstellar medium. GCR composition consists of 89% ionized hydrogen (protons) and 9% ionized helium (alpha particles), with the remaining 2% consisting of heavier ions and electrons. The galactic magnetic field deflects the charged GCRs, thus accelerating them around circular paths – confining them to the disk of the galaxy.

Radioisotope dating has determined that most GCRs have been traveling in our galaxy for tens of millions of years. Their direction has been randomized over time such that they are isotropic. GCRs are traveling at a large fraction of the speed of light, with the majority of particles having kinetic energies of $\sim 1$ GeV. The GCR flux below $\sim 100$ MeV is deflected by the heliosphere. Above 1 GeV, the cosmic ray flux decreases fairly consistently with an increase in particle energy: the higher the energy of the particle, the rarer it is. The highest-energy cosmic rays measured have kinetic energies in excess of $10^{20}$ eV!
Figure 1-3 shows the differential flux of GCRs as a function of particle energy. In comparison, protons emitted from the sun seldom exceed kinetic energies of 1 GeV. The interplanetary magnetic field also influences GCRs within the heliosphere, making it difficult for them to reach the inner solar system. The lower energy range of the GCR flux is modulated by the 11-year solar activity cycle, dropping during maximum solar flux when increased ionization deflects the incoming GCR flux and increasing when the sun is at its minimum activity levels and has less deflective power. The GCR flux varies by a factor of five between solar maximum and minimum conditions.

Solar activity can be divided into three components: solar wind, solar flares and CMEs. The temperature of the sun’s corona is so high that solar gravity cannot keep the energetic particles from escaping. These particles, called the solar wind, stream out of the corona continuously in all directions at speeds ranging from 300-800 km/s. The solar wind consists of highly energized photons, electrons, protons, helium ions and a small number of heavier ions. Solar wind couples to the Earth’s magnetic field and produces storms in the Earth’s magnetosphere. Compared to intense sporadic solar-storm phenomena, the solar wind tends to be significantly less harmful to spacecraft electronics and crews, because most of the flux consists of much lower-energy particles, with a significant portion of the lower-energy flux deflected and trapped by planetary magnetic fields.

In stark contrast, coronal shock waves, prominences, solar flares and CMEs can have a large impact on microelectronic reliability by accelerating solar particles to much higher energies. When viewed head-on, flares manifest as sudden, rapid and intense variations in brightness, which occur when built-up magnetic energy is suddenly released. Flares occur around sunspots where intense and spontaneous discontinuities in magnetic field strength precipitate sudden releases of magnetic energy and plasma stored in the corona, literally shooting large chunks of the coronal surface into space with high velocity. Figure 1-5 shows a photograph of a flare with Earth superimposed to show the scale of typical flare events.

During a flare event, radiation is emitted across the electromagnetic spectrum, from radio waves to gamma rays. As magnetic energy is released during the flare, electrons, protons and heavier nuclei are heated and accelerated to high kinetic energies. CMEs are often associated with solar flares and prominences. As with sunspot activity, the frequency of CMEs varies with the 11-year sunspot cycle. Flares and CMEs are much more frequent during the active phase of the solar cycle. For example, the frequency of CMEs at solar minimum is approximately one CME per week, while at solar maximum, the number of CMEs increases to a couple per day.
Chapter 3: Radiation effects in electronics – dose effects

As illustrated in Figure 3-1, radiation effects impact semiconductor devices in three fundamental ways:

- Single-event effects (SEEs) are random, instantaneous disruptions triggered by the passage of a single particle or photon. One radiation event equals one upset occurrence. An upset could lead to failures in more than one device or bit for each individual radiation event.

- Dose effects are characterized by lasting parametric shifts that accumulate over time due to chronic radiation exposure (a large number of radiation events), ultimately leading the semiconductor device to drift out of tolerance and eventually fail.

- Dose-rate effects entail the delivery of extremely high dose rates (HDRs) over a brief time interval, inducing SEE-like effects.

The focus of this chapter is dose effects. There are two categories of dose effects: total ionizing dose (TID) caused by radiation-induced charge generation/trapping and neutron dose/proton dose (ND/PD) related to the accumulation of physical damage (commonly called displacement damage [DD]) such that electrical properties degrade as the dose increases.

Figure 3-1. A diagram showing the ways in which radiation causes reliability failures in semiconductor devices exposed to radiation.

### 3.1 Total ionizing dose effects

In response to radiation exposure, TID sensitivity can limit product reliability and functionality. At a high level, the key mechanism driving TID is the generation, transport and trapping of holes in the insulation used as gate and isolation oxides in metal-oxide semiconductor (MOS) and bipolar devices at or near the silicon-oxide interface. At a sufficiently high absorbed dose, isolation leakage in complementary MOS (CMOS) circuits will lead to functional failures. In bipolar transistors, oxide charge and interface states in the isolation increase the recombination rate, forcing the base current to increase for a given collector current. In bipolar transistors, TID leads to a reduction in the current gain of the device.

As described in previous chapters, the creation of electronic charge is one of the primary manifestations of radiation’s interaction with matter. Each type of radiation (photons, ions, neutrons, electrons, etc.) loses energy in a variety of different ways and at different rates while traversing matter. The quantity and distribution of excess charge generated in the material is a function of the type of radiation, its energy, its trajectory and its properties. TID is defined as the energy absorbed by a unit mass of material when exposed to ionizing radiation. The overall exposure is quantified in units of radiation-absorbed dose, or rad. A rad is a measure of the absorbed energy per unit mass of a specific material. Originally defined in centimeter-gram-second (cgs) units, a rad is the dose that causes the absorption of 100 ergs by one gram of matter.

Most semiconductor applications report TID as absorbed dose in silicon or rad. The International System of Units uses grays (Gy), with 1 Gy = 100 krad = 1 J/kg. Since most specification and military standards use the older unit of rad, we report all TID in rad(Si) or krad(Si).

In conductor and semiconductor materials such as metals or silicon, respectively, any excess charge generated by the passage of an ionizing radiation event will be largely compensated by recombination, and/or dissipated by drift and diffusion. In other words, in conducting and semiconducting materials, excess charge is effectively transported so that all excess-generated charge is removed from the device in a short time interval. This short-lived charge transient can cause a multitude of SEEs, but from a TID perspective, no charge is accumulated or stored.

The case is radically different for insulating materials. Insulators are characterized by wide band gaps, low free-carrier densities and low carrier mobility, at least for holes. Frequently, the material has a lot of bulk traps. In semiconductor devices, the most common insulator is silicon dioxide (SiO₂), which is used to form the gates of MOS transistors and as isolation material in both MOS and bipolar technologies. The absorption of energy from radiation exposure creates a number of effects in the oxide that degrade device performance and potentially its functionality.

Figure 3-2 is a band diagram of the MOS stack that forms metal-oxide semiconductor field-effect transistors (MOSFETs) and bipolar junction transistors (BJTs), illustrating excess charge generation by exposure to radiation, and the subsequent transport and trapping of that excess charge at or near the interface in SiO₂ on silicon. The diagram represents distance (or depth) on the horizontal axis and electron energy on the vertical axis. More energetic electrons appear higher on the diagram, and a positive voltage pulls the energy bands down. The positively biased polysilicon (or metal) gate electrode is shown on the left, with the insulator layer in the middle. The insulator energy bands are slanted electric field from the gate and silicon electrodes. Energy from incident radiation is absorbed in the insulator by the formation of electron-hole (e-h) pairs. Approximately 17 eV of energy is required for the production of each single e-h pair in oxide. The creation of excess charge occurs on the femtosecond timescale.
These localized structural deformations are called small polarons. The holes are effectively self-trapped in the oxide by virtue of the polaron formation. The holes do migrate – by drift and diffusion – but relatively slowly, “hopping” from adjacent shallow traps in the valence band and carrying the polaron with them as they move.

The hopping process breaks chemical bonds, releasing trapped protons (H⁺). These protons are free to diffuse or “drift” in the same direction as the holes. The migration of holes and protons to the oxide interface occurs over a time frame of seconds. Ultimately, holes that migrate toward the SiO₂-silicon interface get captured by mid-band-gap traps near the interface – initially causing a positive charge buildup – or are captured at the interface itself, where they create interface states that are positive, neutral or negative. The deep-hole traps reside in the oxide one or more atomic spacings away from the SiO₂-silicon interface.

Hole traps are created by naturally occurring defects that appear when excess silicon from the substrate diffuses into the oxide and creates oxygen vacancies (oxygen-depleted oxide = SiOₓ, where x < 2). These oxygen vacancies form hole traps that are energetically deep so that at room temperature, the thermal energy is not large enough to cause hole release from the traps. The trapped holes are relatively stable and generally immobile.

Holes trapped at the oxygen vacancies are responsible for an accumulated positive charge in MOS and bipolar devices during irradiation. Tunneling or thermalized electrons injected from the silicon that neutralize the hole charge compensate for the positive hole charge. In such cases, the hole can recombine with the injected electron and permanently remove the charge. The normal bonding structure is re-established to an unoccupied oxygen vacancy; thus the defect is considered to be “annealed out.”
In other cases, the hole and electron do not recombine but form a dipole pair that can be polarized. Often referred to as border traps, these oxide traps exchange charge with the silicon substrate and can act as a neutral, positive or negative charge. This complex set of charge states explains “rebound behavior” – the instability in the TID-induced threshold voltage shift – observed in MOS transistors as a function of bias and temperature after radiation exposure. SiO₂, grown even under the best conditions, has a certain density of surface structural defects at the interface between the oxide and the silicon. In bulk silicon, every silicon atom is covalently bonded to each of its four nearest neighbors.

At the transition between pure silicon and SiO₂, a region of oxygen vacancies forms on the oxide side. At the actual surface where the silicon meets the oxide, less-stable trivalent silicon complexes form where the silicon atom only bonds to three other silicon atoms, leaving one of its four available bonds free or dangling. This dangling bond is electrically active and can interact with carriers in the silicon substrate near the interface. In normal semiconductor processing, hydrogen passivation hides these defects when hydrogen forms a stable bond. Released during hole transport, protons reaching the interface depassivate the bonded hydrogen, re-establishing dangling bonds that once again become electrically active.

Radiation-induced interface traps at the silicon-SiO₂ interface induce voltage-dependent threshold shifts – positive or negative depending on bias – just like the trapped-hole charge. In addition, these shifts increase surface recombination rates while decreasing carrier mobility. Both the trapped-hole charge and interface-state charge cause dose-dependent device marginalities in both MOS and bipolar devices. Rebound or super-recovery is the reduction and eventual reversal of the initial threshold voltage shift induced immediately after a radiation exposure. It is primarily a concern in MOS devices, where strong bias (a high electric field) is usually present in the gate oxide.

\[ \text{Figure 3-4} \] illustrates the time evolution of the threshold voltage, \( V_T \), and the change in \( V_T \) due to changes in the number of deep-oxide hole traps and interface states (\( \Delta V_T \) and \( \Delta V_{IT} \), respectively).

This experiment was repeated at two different annealing temperatures. During irradiation, interface-state charge and oxide-trapped charge accumulate. Immediately after exposure, the positive trapped-hole charge dominates and the NMOS \( V_T \) decreases. Leakage increases, and the transistor is easier to turn on. After irradiation with a positive gate bias, electrons from the silicon tunnel into the oxide and neutralize the trapped-hole charge through the recombination of electrons that tunnel to the holes and the formation of trapped dipoles. The annealing process is defined by compensation of the positive hole charge such that the typically negative interface-state charge dominates, thereby increasing \( V_T \).

This radiation-induced shift, followed by a shift the other way during annealing, is known as rebound. Rebound is really limited to older (thick) oxide processes and does not occur in modern MOSFET processes. The magnitude of the rebound depends on temperature and bias. Increasing temperature increases the annealing rate of oxide-trapped charge, but generally has a much less pronounced effect on surface-state annealing. The rebound effect is minimized in oxide processes where the density of interface states is inherently low.

As part of the standard radiation-hardness-assured (RHA) flow, Texas Instruments tests for rebound according to military standard (MIL-STD)-883E 1019.9 (3.12.2B)\[3\], with 168-hour annealing at 100°C under worst-case bias conditions after post-irradiation characterization to determine the magnitude of the rebound if it occurs. Degradation due to TID presents one additional complication primarily affecting bipolar devices. Dose-rate sensitivity effects are not usually associated with MOSFETs, which can typically be accurately characterized at HDRs. Some bipolar devices suffer significantly more degradation when radiation exposure occurs at a low dose rate (LDR). In other words, dose rates that accumulate slowly cause more degradation than if the same device had been exposed at an HDR.

This LDR effect or enhanced low-dose-rate sensitivity (ELDRS) is a feature observed in some bipolar devices and thus requires validation on any new device.\[4-7\] Understanding if a device has ELDRS is critical because the actual dose rates encountered in most radiation environments, including space environments, are very low. Conducting HDR tests only on devices with ELDRS would lead to significantly underestimated TID sensitivity. A device thought to be robust to TID would actually fail long before it was expected to based on HDR results alone.

The plot in \[ \text{Figure 3-5} \] shows several bipolar devices tested to the same TID level using a large range of dose rates. Clearly, there is a wide range of ELDRS sensitivity for different devices: LMS24 devices are very dose-rate sensitive, while LM108 devices appear to have no sensitivity to dose rate at all. ELDRS and TID are extremely sensitive to the process used to form and anneal the oxides; thus the same device from two different vendors (even two devices from the same vendor but manufactured at two different sites) can have altogether different TID and dose-rate dependencies. One of the onerous aspects of ELDRS testing is the long irradiation times required. HDR testing, with a typical dose rate in the range of ~100 rad/s, takes approximately 20 minutes to reach 100 krad(Si). In contrast, the same 100-krad(Si) target dose takes approximately 116 days, or nearly four months at the typical
Chapter 5: Radiation sensitivity by technology

A microcircuit’s radiation tolerance is dependent upon many variables. This chapter will mainly focus on a product’s sensitivity to radiation at a macro level, discussing general trends such as process technology and operating conditions. The next chapter will delve more deeply into the physics of radiation sensitivity and radiation mitigation techniques.

Some semiconductor technologies and process nodes (feature sizes) tend to be softer to radiation than others. But at the same time, it is important to note that two similar processes on the same technology node could have very different radiation responses.

Also, the wafer fab process is not the only determining factor for radiation hardness. Two products that share the same process can have very different radiation responses. Ultimately, semiconductor suppliers of radiation tested products have a better understanding of which processes and products are likely to be more radiation tolerant.

5.1 Total ionizing dose

In complementary metal-oxide semiconductor (CMOS) processes, the reduction in feature sizes over the years has generally resulted in an improvement in total ionizing dose (TID) survivability. Because ionizing radiation charges dielectrics, sensitivity to TID will depend on susceptible dielectric volume, its location and its influence on active circuits. In older CMOSs with thick gate oxides and long channel lengths, ionizing radiation could cause threshold-voltage shifts.[1]

As gate thicknesses, voltages and feature sizes decreased and the composition of gate dielectrics changed, the impact of ionizing radiation on threshold voltage lessened. The limiting factor on TID survivability became the field oxide; charged field oxide created leakage paths underneath the oxide.[2-4]

The prevailing technology for CMOS field oxide in the 1980s and 1990s was the local oxidation of silicon (LOCOS) process (Figure 5-1). Due to many factors in the process and structure, LOCOS was very soft to ionizing radiation.[5] The grown LOCOS edge profile had a characteristic “bird’s-beak” at the channel edge, which induced local electric fields that were very effective at attracting positive-hole-charge TID radiation exposure generated throughout the LOCOS volume. This hole charge attracted electrons in the n-channel MOS (NMOS) region and caused off-state leakage to result in functional failures at relatively low doses.

To accommodate scalability as process nodes dropped below 350 nm, the LOCOS process was replaced with shallow trench isolation (STI) where a trench is etched between transistors and then filled by deposited films (Figure 5-1).

STI does not give immunity to isolation leakage issues, but by managing the sidewall profile and the quality and morphology of the deposited dielectrics, TID in technologies with STI will often be much better than a similar technology with LOCOS isolation.

The increased channel doping, thinner gate oxide and lower operating voltages all contribute to enhance robustness against TID in modern CMOS technologies. As illustrated in Figure 5-2, as feature sizes have reduced, TID performance has improved dramatically, largely due to the migration from LOCOS to STI. Use caution when assuming that an STI technology will automatically provide a high TID performance – the scatter in the data indicates that the physical properties and morphology of STI has a large effect on the final TID performance in MOSFET devices.[5, 6]

The level of TID that a CMOS product can survive depends on the dose rate the device receives. Because of self-annealing effects, CMOS products can withstand a much higher TID at low dose rates than at high dose rates. The Texas Instruments (TI) DAC121S101QML-SP space-grade precision digital-to-analog converter can fail at a dose below 30 krad(Si) when irradiated at a dose rate above 50rad(Si)/s and survive doses greater than 100 krad(Si) when irradiated at a lower dose rate of 0.01 rad(Si)/s (Figure 5-3). [7]
CMOS impact of bias voltage

The bias voltage to which a device is subjected during irradiation also impacts CMOS sensitivity to ionizing radiation. A higher bias voltage will result in more charge buildup in the oxides. Analog CMOS products with wide operating voltage ranges will tend to survive a higher TID level when operating at lower voltages during irradiation.

The Texas Instruments DAC121S101QML-SP will fail at a TID lower than 30 krad(Si) when biased at the maximum operating voltage of 5.5 V during irradiation at an HDR. The device will pass at greater than 100 krad when biased at 3.3 V during irradiation at any dose rate. A device not biased during irradiation can survive a much higher TID level — in some cases an order of magnitude or more higher — than a device biased during irradiation. As feature sizes shrank, so did gate voltages in digital devices, which led to lower supply voltages and higher TID level survivability.[9]

CMOS impact of process nodes/feature size

In general, CMOS process nodes above 1 µm are fairly soft to ionizing radiation, failing at TID levels below 30 krad(Si) and sometimes lower than 3 krad(Si). As process nodes dropped below 1 µm, some products began surviving levels as high as 100 krad(Si), especially at LDRs. Power processes such as high-voltage N-channel MOSFET and double-diffused MOS tend to perform similarly to the larger CMOS process nodes. At the 180-nm node, it is typical for a product to pass 100 krad(Si) even at HDRs.

Deep submicron structures (90 nm and below) routinely are good to 300 krad or even into the Mrad levels. The exception is fully depleted CMOS structures on SOI substrates. Charging of the buried oxide can impact these structures.[9]

Deep submicron processes can also have higher voltage modules, with larger feature sizes and higher gate voltages. If you use these higher-voltage modules, they can become the limiting factor of the TID level of a product. For instance, Texas Instruments’ space-grade ADC08D1520QML-SP and ADC14155QML-SP analog-to-digital converters are on the same CMOS 180-nm process. The ADC08D1520QML-SP only uses minimum-geometry 1.9-V cells and is rated to 300 krad. The ADC14155QML-SP also uses the 3.3-V modules available on this process and is rated to 100 krad.[7]

Classic linear bipolar products

Unlike CMOS processing, gradual evolutionary changes in bipolar process technology have had little impact on TID survivability. The classic junction-isolated bipolar integrated circuit (IC) has been around since the late 1960s. It features vertically integrated NPN transistors and may have additional elements such as junction resistors, MOS capacitors, bipolar FETs and horizontal PNP transistors. Some products also have inefficient vertical PNP transistors using the base area and substrate.

The minimum-sized feature is the metal-to-silicon contact or width of the junction resistor or metal lines, and is measured in microns. For instance, the minimum geometry of the LM139 is 10 µm. Products were generally handcrafted with unique layouts and changes to junction profiles to meet performance needs.

It has been stated that bipolar processes use low-quality oxide, which has led to poor TID performance and dose-rate issues.[10] In reality, bipolar process oxides were specifically engineered to provide the highest gain transistors with the highest breakdowns and lowest leakage possible. What is optimal for transistor performance in an analog circuit is not necessarily optimal for radiation hardness.

The TID survivability of classic bipolar analog products ranges from 1 to 100 krad(Si). TID performance can depend on the bipolar process, but also on the function of the device, the layout of the transistors and metal routing. Two products on the same process can have significantly different TID survivability levels. Texas Instruments’ LM2941 and LP2953 space-grade low-dropout regulators (LDOs) have the same process, but different TID ratings (Table 1).
The different manufacturing improvements of bipolar products over the years might not have any impact on the TID response, or could have adverse effects. For example, in the early 1980s, a layer of silicon nitride was added to the top passivation as an excellent moisture barrier, which resulted in significant improvements to product reliability. But that additional layer of silicon nitride also resulted in the degradation of TID performance of many bipolar products.[11]

Improvements in process controls have enabled a reduction in feature sizes, and the LM139QML-SP from Texas Instruments has gone through several die shrinks since its release in 1972. The last die shrink, released in the 2000 time frame, made TID performance worse[12] because of changes in transistor sizes, shapes and metal routing. In addition to the changes detailed in reference,[13] a number of additional steps were required to return the space-grade LM139AQML-SP back to its pre-shrunk die radiation performance.

**Enhanced low dose rate sensitivity**

Many classic linear bipolar products have been shown exhibit Enhanced Low Dose Rate Sensitivity (ELDRS) where more degradation from ionizing radiation is seen when a product is irradiated at low dose rate than when at high dose rate (see Chapter 3). It is not possible to predict which products will show ELDRS, although the addition of the nitride passivation layer can enhance this phenomenon.[11]

As an example, some versions of the LM111 comparator have ELDRS, where the input bias current drifts higher when irradiated at an LDR of 0.01 mrad/s than when irradiated at 50 rad/s (Figure 5-4).[13] The space-grade LM111 from Texas Instruments does not exhibit ELDRS (Figure 5-5).[14]

Some bipolar products behave like CMOSs and actually have less degradation at LDRs. The Texas Instruments space-grade LM111 comparator is rated to only 50 krad at an HDR, while it is rated to 100 krad at an LDR (Figure 5-6).[14] For some products, certain parameters will be worse at an LDR, while other parameters of the same device will be worse at an HDR. The only way to know if a classic bipolar product has ELDRS is to test it at an LDR.

Unlike CMOS processes, it is difficult to predict how biasing will impact the performance of a linear bipolar product. For some products, being irradiated while unpowered is the worst case, especially at LDRs. For example, in the Texas Instruments LM117HVQML-SP space-grade adjustable high-voltage regulator, irradiating the unbiased device is the worst case for voltage reference (VREF) drift (Figures 5-6 and 5-7). On the LM2941QML-SP space-grade adjustable LDO, the output voltage drifts lower when the device is unbiased during irradiation, but drifts higher when powered up during irradiation (Figure 5-8).[15,16]
Glossary

Alpha particle
The nucleus of a helium atom, consisting of two protons and two electrons. Type of radioactive decay.

Bias voltage
Voltage applied to a node of an electronic device.

Bragg peak
Depth in silicon where most of an ion’s energy is deposited.

Bremsstrahlung
An X-ray emitted due to an electron losing speed during a collision with a nucleus.

Carrier recombination
When holes and electrons combine, resulting in no charge.

Corona
Outer layer of the sun.

Coronal mass ejection
When significant amounts of plasma and magnetic field are released from the solar corona.

Coulombic interactions
Interactions between charged particles, either attraction or repulsion.

Cross-section
In single-event effect testing, the number of errors per area of a device.

Deep trench isolation
A deep trench etched in silicon and then filled with oxide to separate transistors.

Die
An individual integrated circuit, not including packaging.

Diffusion lot
A group of wafers that went through the wafer fab diffusion process at the same time, in the same diffusion tube; may also be called a wafer lot.

Displacement damage dose
Radiation with particles of enough energy and mass to cause damage to the lattice of a semiconductor.

Dose-rate effects
Impact on a device from a very high radiation dose rate. Also known as prompt dose.

Effective linear energy transfer
A calculation of the total energy deposited in a volume for particles that impact the volume at an angle. This calculation is not valid for all microcircuit devices.

Electromagnetic waves
Waves of energy, including radio waves, microwaves, infrared waves, visible light, ultraviolet light, X-rays and gamma rays. The physical counterpart is photons.

Enhanced low-dose-rate sensitivity
Indicates that a device can tolerate a higher total ionizing dose at a high dose rate than at a low dose rate.

Fluence
Total number of particles to hit an area.

Flux
Movement or rate of movement. In heavy-ion testing, the flux is the number of ions hitting a unit area in a unit amount of time.

Free path
How far a particle can travel before colliding into another particle.

Galactic cosmic ray
Energetic atom fragments, which can be nuclei, protons or electrons.

Geostationary orbit
Around 20,000 miles from the Earth’s surface. The orbit is the same as the Earth’s rotation; therefore, a satellite is always in the same place relative to a point on the Earth’s surface.

Heavy ion
A charged atom heavier than helium. For radiation testing, they are positively charged due to the loss of one or more electrons. A helium ion is known as an alpha particle.

Ion
A negatively or positively charged particle.

Ion run
Time from when the ion beam is turned on to when it is turned off; also known as a beam run.

Integrated circuit
Also known as a computer chip.

Linear energy transfer
The amount of energy a particle deposits in a substance.

Local oxidation of silicon
The growth of field oxide to separate N-channel and P-channel devices in a complementary metal-oxide semiconductor process.

Lot
A group of units that were processed together. A lot could be the die from a single wafer, a group of wafers or a group of units that were assembled at the same time.

Low Earth orbit
About 60 to 1,200 miles from the Earth’s surface.

Medium Earth orbit
About 1,200 to 22,000 miles from the Earth’s surface.

Multiple-bit upset
When more than one cell is upset from an ion strike.

Nonionizing energy loss
Radiation from a nonionizing particle, such as a neutron.

Prompt dose
A very high radiation dose rate, typically from a nuclear detonation. Also known as dose rate effects.

Rad
Unit of ionizing radiation absorbed.

Radiation
Transport of energy from one location to another, where the carriers are photons, ions, electrons, muons and/or nucleons (neutrons or protons).

Radiation hardened
Changes to a product that make it more tolerant to radiation, but sometimes just referring to a product that is radiation tested.
Radiation hardness by design
Designing a part for improved tolerance to radiation.

Radiation hardness by process
Creating a wafer fab process to improve tolerance to radiation.

Radiation lot acceptance test
Radiation test performed on a lot of material to verify that it meets the specified radiation level.

Radioactive decay
When an unstable atom loses energy through its core, emitting particles.

Sensitive volume
The region of a microcircuit where a particle strike can cause a single-event effect.

Shallow trench isolation
A shallow trench etched into silicon and then filled with oxide to separate N-channel and P-channel devices in a complementary metal-oxide semiconductor process.

Single-event burnout
Damage to a circuit from excess current flow due to an ion strike, typically in a metal-oxide semiconductor transistor.

Single-event effect
What happens when a particle hits a microelectronic circuit or component.

Single-event functional interrupt
Change in the operating mode of an integrated circuit due to a particle strike. Originally meaning a change in a setup register, it now commonly refers to any change, such as an integrated circuit going into reset.

Single-event gate rupture
Damage to the gate oxide of a metal-oxide semiconductor device from a particle strike.

Single-event latch-up
When a parasitic thyristor turns on due to a particle strike. The thyristor will remain on until supply voltage is removed.

Single-event phenomena
Same as a single-event effect.

Single-event transient
A voltage pulse caused by a particle strike.

Single-event upset
A change in the state of a digital circuit caused by a particle strike. Sometimes used to cover many different types of nondestructive single-event effects.

Solar flares
Sudden burst in the sun’s brightness; sometimes accompanied by a coronal mass ejection, which increases the number of charged particles in the solar wind.

Solar wind
Stream of charged particles emitted into space from the sun.

Standard microcircuit drawing
Device information and specifications maintained by the Defense Logistics Agency.

System-on-chip
An integrated circuit with many functions; all components are implemented within the chip silicon.

Total ionizing dose
Amount of a radiation that a device has received.

Van Allen radiation belt
Area around the Earth where energetic particles, mostly from solar winds, are captured by the Earth’s magnetic field.
### Acronyms

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Definition</th>
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<tbody>
<tr>
<td>ADC</td>
<td>analog-to-digital converter</td>
</tr>
<tr>
<td>AMU</td>
<td>atomic mass unit</td>
</tr>
<tr>
<td>ASET</td>
<td>analog single-event transient</td>
</tr>
<tr>
<td>ASTM</td>
<td>American Society for Testing and Materials</td>
</tr>
<tr>
<td>ATE</td>
<td>automated test equipment</td>
</tr>
<tr>
<td>BiCMOS</td>
<td>bipolar complementary metal-oxide semiconductor</td>
</tr>
<tr>
<td>BJT</td>
<td>bipolar junction transistor</td>
</tr>
<tr>
<td>BL</td>
<td>bitline</td>
</tr>
<tr>
<td>BOX</td>
<td>buried oxide</td>
</tr>
<tr>
<td>BPSG</td>
<td>boron-doped phosphosilicate glass</td>
</tr>
<tr>
<td>CAT</td>
<td>computerized axial tomography</td>
</tr>
<tr>
<td>CCD</td>
<td>charge-coupled device</td>
</tr>
<tr>
<td>CMEs</td>
<td>coronal mass ejections</td>
</tr>
<tr>
<td>CMOS</td>
<td>complementary metal-oxide semiconductor</td>
</tr>
<tr>
<td>COTS</td>
<td>commercial off-the-shelf</td>
</tr>
<tr>
<td>CT</td>
<td>computer tomography</td>
</tr>
<tr>
<td>DBU</td>
<td>double-bit upset</td>
</tr>
<tr>
<td>DD</td>
<td>displacement damage</td>
</tr>
<tr>
<td>DDD</td>
<td>displacement damage dose</td>
</tr>
<tr>
<td>DEC-TED</td>
<td>double-error correct-triple-error detect</td>
</tr>
<tr>
<td>DICE</td>
<td>dual interlocked storage cell</td>
</tr>
<tr>
<td>DMOSFET</td>
<td>double-diffused metal-oxide semiconductor field-effect transistor</td>
</tr>
<tr>
<td>DMR</td>
<td>dual-modular redundant</td>
</tr>
<tr>
<td>DRAM</td>
<td>dynamic random access memory</td>
</tr>
<tr>
<td>DSET</td>
<td>digital single-event transient</td>
</tr>
<tr>
<td>DTI</td>
<td>deep trench isolation</td>
</tr>
<tr>
<td>DUT</td>
<td>device under test</td>
</tr>
<tr>
<td>e-h</td>
<td>electron hole</td>
</tr>
<tr>
<td>ECC</td>
<td>error correction circuit</td>
</tr>
<tr>
<td>ELDERS</td>
<td>enhanced low-dose-rate sensitivity</td>
</tr>
<tr>
<td>EMP</td>
<td>electromagnetic pulse</td>
</tr>
<tr>
<td>ESA E</td>
<td>European Space Agency</td>
</tr>
<tr>
<td>ESCC</td>
<td>European Space Components Coordination</td>
</tr>
<tr>
<td>FET</td>
<td>field-effect transistor</td>
</tr>
<tr>
<td>FIT</td>
<td>failures in time</td>
</tr>
<tr>
<td>FPGA</td>
<td>field-programmable gate array</td>
</tr>
<tr>
<td>GCR</td>
<td>galactic cosmic ray</td>
</tr>
<tr>
<td>GEO</td>
<td>geostationary orbit</td>
</tr>
<tr>
<td>GSO</td>
<td>geosynchronous orbit</td>
</tr>
<tr>
<td>Gy</td>
<td>grays</td>
</tr>
<tr>
<td>hFE</td>
<td>bipolar transistor gain</td>
</tr>
<tr>
<td>IC</td>
<td>integrated circuit</td>
</tr>
<tr>
<td>IGBT</td>
<td>insulated gate bipolar transistor</td>
</tr>
<tr>
<td>LBNL</td>
<td>Lawrence Berkeley National Labs</td>
</tr>
<tr>
<td>LDO</td>
<td>low-dropout regulator</td>
</tr>
<tr>
<td>LDR</td>
<td>low dose rate</td>
</tr>
<tr>
<td>LEO</td>
<td>low Earth orbit</td>
</tr>
<tr>
<td>LET</td>
<td>linear energy transfer</td>
</tr>
<tr>
<td>LOCOS</td>
<td>local oxidation of silicon</td>
</tr>
<tr>
<td>MAAT</td>
<td>metal-oxide semiconductor accelerated anneal test</td>
</tr>
<tr>
<td>MBU</td>
<td>multiple-bit upset</td>
</tr>
<tr>
<td>MCU</td>
<td>multicell upset</td>
</tr>
<tr>
<td>MEO</td>
<td>medium Earth orbit</td>
</tr>
<tr>
<td>MIL-STD</td>
<td>military standard</td>
</tr>
<tr>
<td>MOS</td>
<td>metal-oxide semiconductor</td>
</tr>
<tr>
<td>MOSFET</td>
<td>metal-oxide semiconductor field-effect transistor</td>
</tr>
<tr>
<td>MUX</td>
<td>multiplexer</td>
</tr>
<tr>
<td>ND/PD</td>
<td>neutron dose/proton dose</td>
</tr>
<tr>
<td>NIEL</td>
<td>nonionizing energy loss</td>
</tr>
<tr>
<td>NMOS</td>
<td>N-channel metal-oxide semiconductor</td>
</tr>
<tr>
<td>NPN</td>
<td>N-channel P-channel N-channel</td>
</tr>
<tr>
<td>NYC</td>
<td>New York City</td>
</tr>
<tr>
<td>OM</td>
<td>optical microscope</td>
</tr>
<tr>
<td>PMOS</td>
<td>P-channel metal-oxide semiconductor</td>
</tr>
<tr>
<td>PNP</td>
<td>P-channel N-channel P-channel</td>
</tr>
<tr>
<td>PNPN</td>
<td>P-channel N-channel P-channel N-channel</td>
</tr>
<tr>
<td>QML</td>
<td>Qualified Manufacturers List</td>
</tr>
<tr>
<td>R</td>
<td>read</td>
</tr>
<tr>
<td>RFID</td>
<td>radio-frequency identification</td>
</tr>
<tr>
<td>RHA</td>
<td>radiation hardness assured</td>
</tr>
<tr>
<td>RHBD</td>
<td>radiation hardening by design</td>
</tr>
<tr>
<td>RHBP</td>
<td>radiation hardening by process</td>
</tr>
<tr>
<td>RLAT</td>
<td>radiation lot acceptance testing</td>
</tr>
<tr>
<td>SAA</td>
<td>South Atlantic Anomaly</td>
</tr>
<tr>
<td>SBU</td>
<td>single-bit upset</td>
</tr>
<tr>
<td>SEB</td>
<td>single-event burnout</td>
</tr>
<tr>
<td>SEC-DED</td>
<td>single-error correct-double-error detect</td>
</tr>
<tr>
<td>SEDR</td>
<td>single-event dielectric rupture</td>
</tr>
<tr>
<td>SEE</td>
<td>single-event effect</td>
</tr>
<tr>
<td>SEFI</td>
<td>single-event functional interrupt</td>
</tr>
<tr>
<td>SEGR</td>
<td>single-event gate rupture</td>
</tr>
<tr>
<td>SEL</td>
<td>single-event latch-up</td>
</tr>
<tr>
<td>SEM</td>
<td>scanning electron microscope</td>
</tr>
<tr>
<td>SEP</td>
<td>solar energetic particles</td>
</tr>
<tr>
<td>SER</td>
<td>soft-error rate</td>
</tr>
<tr>
<td>SET</td>
<td>single-event transient</td>
</tr>
<tr>
<td>SEU</td>
<td>single-event upset</td>
</tr>
<tr>
<td>Si</td>
<td>silicon</td>
</tr>
<tr>
<td>SiGe</td>
<td>silicon germanium</td>
</tr>
<tr>
<td>SMD</td>
<td>standard microcircuit drawing</td>
</tr>
<tr>
<td>SOA</td>
<td>safe operating area</td>
</tr>
<tr>
<td>SoC</td>
<td>system-on-chip</td>
</tr>
<tr>
<td>SOI</td>
<td>silicon-on-insulator</td>
</tr>
<tr>
<td>SOS</td>
<td>silicon-on-sapphire</td>
</tr>
<tr>
<td>SRAM</td>
<td>static random access memory</td>
</tr>
<tr>
<td>SRIM</td>
<td>Stopping and Range of Ions in Matter</td>
</tr>
<tr>
<td>STI</td>
<td>shallow trench isolation</td>
</tr>
<tr>
<td>TAMU</td>
<td>Texas A&amp;M University</td>
</tr>
<tr>
<td>TDE</td>
<td>time-dependent effect</td>
</tr>
<tr>
<td>TEM</td>
<td>transmission electron microscope</td>
</tr>
<tr>
<td>TID</td>
<td>total ionizing dose</td>
</tr>
<tr>
<td>TM t</td>
<td>est method</td>
</tr>
<tr>
<td>TMR</td>
<td>triple-modular redundant</td>
</tr>
<tr>
<td>TPA</td>
<td>two-photon absorption</td>
</tr>
<tr>
<td>ULA</td>
<td>ultra-low alpha</td>
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<tr>
<td>W</td>
<td>write</td>
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<tr>
<td>WL</td>
<td>wordline</td>
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