

Radiation Effects in Integrated Circuits, and Radiation Hardening Techniques

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Abstract
Radiation from natural and artificial elements bombards the earth The radiation environment depends on energy distribution and particle spectra. Radiation affects most electronic components, especially ICs (ICs). High nuclear reactors and space radiation damage electronic components, but the earth's electronic components also do. Semiconductors are radiation-sensitive, hence ICs need radiation shielding. The operation and performance of devices are affected by these effects. Radiation type, energy, flux, and exposure period affect damage. Gamma rays and neutrons are indirect ionizing radiation. These beams harm silicon-based semiconductors like transistors. Radiation can damage semiconductors, especially ICs. As a result of displacement damage and ionizing radiation, semiconductors degrade in three devices. Insulator traps charge. (2) minor carrier recombination modifications Various-energy particles generate different ionization and displacement damage. In the research of radiation effects and consequences, it's vital to look at how radiation affects semiconductors and integrated circuits. Radiation hardening decreases radiation damage. Radiation hardening renders electronics ionizing or non-ionizing radiation-resistant. To assure appropriate operation, IC, sensor, and military aircraft makers adopted hardening.
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1. Introduction

The earth is exposed to radiation and it both occurs naturally from minerals and man-made elements. Generally, the radiation environments include space, High-energy physics experiments, Nuclear, Natural environments, and processing-induced radiation. Energy distribution and spectrum of particles determine the type of radiation environment. The problems that affect the reliability of most electronic components, especially Integrated Circuits (ICs) are associated with radiation effects. Though the radiation from space and high nuclear reactors processes severe effects on electronic components, the electronic components from the earth also exhibit some errors that reduce their performance. This creates serious design challenges for ICs [1], [2]. Generally, ICs are made up of semiconductor devices and these devices would not survive if they were not protected against radiation. Chapter 1 describes the radiation effects classification on electronic components, including mechanisms of radiation interaction with matters, displacement damage, total ionization, and single event effects. These effects change the devices' functionality and performance, but the damage depends on radiation type, energy, flux, and exposure duration. The alpha and beta particles are classified as direct ionizing radiation while the gamma rays and neutron radiation are from indirect ionizing radiation, and they are mostly causing damage to semiconductors which are made of silicon and make up most terrestrial electronic components such as transistors [1], [3]. Most electronic semiconductor components particularly (ICs) are vulnerable to radiation. The process through which they become more resistant to radiation damage is a technique known as radiation hardening. Radiation hardening consists of designing and manufacturing electronic devices and systems which are tolerant to non-ionizing radiation and ionizing radiation. Therefore, many techniques were carried out by different ICs, sensors, and military aerospace manufacturers to ensure proper operation by using hardening techniques. Chapter 3 classifies rad-hardening techniques into physical and logical radiation hardening types and they are explained in detail [4].

2.0 Related Literature

2.1. Overview of radiation particles and Mechanisms

Radiation includes alpha (), beta (), gamma (), x-rays, and neutron particles. These types of particles can be divided into three groups based on their interaction with target materials: [3] with neutrons, protons, alpha particles, and other heavy atoms, non-ionization processes induce displacements in target materials, which destroys electrical equipment. Ionization processes involve x-rays and alpha particles passing through electronic equipment, forming electron-hole pairs in particles. Ionizing radiation can ionize atoms. This form of ionization can irreversibly destroy a device if it accumulates too many particles [5]. Figure 1 compares two ionization processes.

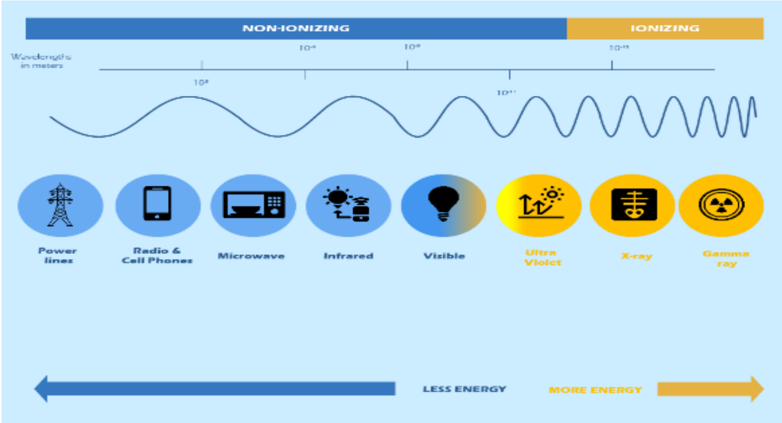

Figure 1: Non-ionization Vs ionization radiation processes

2.2. Radiation-induced defects and their properties

2.2.1. The radiation damage mechanism in integrated circuits

Semiconductor materials, integrated circuits, and bipolar devices like NPN bipolar junction transistors (BJTs) are used in spacecraft because of their current driving capabilities and excellent matching. Semiconductor devices can be damaged and fail when exposed to space's harsh, dangerous environment beyond a specific threshold of energetic charged particles. The effect of this radiation on devices can be investigated with protons, neutrons, electrons, and 60Co gamma rays [6]. These heavy-ion radiation effects help comprehend radiation damage. In contrast, not enough research has been done on radiation's effects on bipolar ICs' electrical devices. So, displacement damage and ionizing radiation destroy semiconductors, especially bipolar devices, by three processes: (1) Charge traps on the surface of an insulator. (2) Surface recombination of minor carriers. (3) Large-scale damage [7]. Incident particles contribute to ionization and displacement damage with varying energies. Radiation must be studied to find out how it affects semiconductors and integrated circuits and what it means.

2.2.2 Displacement Damage

This kind of damage harms the semiconductors with silicon and is mainly caused by the long-term non-ionizing effect as discussed above in the previous chapter. The long-term non-ionizing effect is the main cause of displacement damage and occurs in the case of an incident particle having enough energy to knock an atom free from its normal lattice site in the semiconductor. This damage changes devices' operations working operation due to some factors including thermal charge generation, high leakage current, and low minority carrier movement. Generally, the electrical degradation effects can be classified into the following categories: Long-term radiation effect, Generation and recombination of Electronic-Hole pairs by radiation-induced defects, Carriers trapping caused by radiation-induced defects, Compensation donors and acceptors, Carriers tunneling

And these categories can be identified schematically in figure 2.

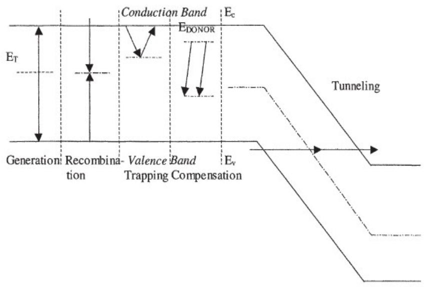

Figure 2: Basic effects of a radiation-induced defect level (E_T) on electronic device performance [2].

Table 1 shows the research history of displacement damage up to the 21st century [3].

1. Period	2. Details on Displacement damage defects for electronic devices
3. 1963-1972	4. Displacement effects in different semiconductor materials and devices
5. 1973-1982	6. Exploring displacement effects on advanced devices and circuits, Integrated-injection, and charge-coupled devices (CCDs)
7. 1983-1992	8. Analysis of displacement effects on MOS devices and circuit technologies, solar cells, GaAs devices, particle detectors, photodiodes, and BJTs.
9. 1993-2002	10. Grappling various semiconductor devices and materials, and the non-ionizing energy loss (NIEL), damage correlation, and synergistic effects.
11. 2003-2012	12. Effects in SDRAMs and memory devices as well as their computational analysis.

2.2.3 *Total Ionizing Doze Effects*

The total amount of energy settled by radiation particles passing through semiconductor material is called the total ionizing dose (TID) [3, 8]. When the radiation dose reaches 104–108 rad (Si), it's in the strong radiation environment detailed in chapter 1. TID generates ionization of lattice atoms or lattice defects by removing atoms from their usual lattice locations [9]. Figure 2 shows how ionizing particles hit silicon dioxide (SIO2). First, energy deposited in the semiconductor material creates electron-hole pairs (EHPS), and some of them recombine. Second, free carriers escape recombination and move into the oxide. Third, hole trapping at the SiO2/Si interface creates a trapped charge (fixed charge), and fourth, hole interactions create interface traps [3].

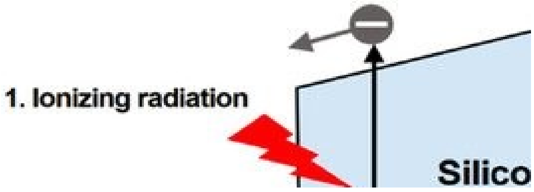

Figure 2: Diagram showing the radiation-induced fixed charges in SIO2 originated from the TID effect [3].

As discussed earlier, in MOS devices which include transistors and ICs, ionizing radiation affects their performance properties including mobility degradation, high level of leakage currents, high resistance, breakdown voltage reduction, increased gate charge, and threshold voltage shifts [3], [10].

2.2.4 Single effect

This type of physical mechanism event is an instantaneous temporary or permanent damage imposed by a particle strike that finally causes soft errors or burns to electronic devices [9]. Generally, the single event mechanism takes 3 steps. The second step is charge transport where the released carriers are collected and moved by element structures that include p-n junctions. The last step is the charge collection where the electronic components are disturbed due to the parasitic current and this causes permanent damage to the gate insulators. According to the reaction status of the semiconductor device, the single event effects can also be classified into 2 categories. These are non-destructive and destructive effects, and they are detailed in the following sections.

2.2.4.1 Non-Destructive Effect

This happens when the semiconductor can be recovered from the failure generated by a single event effect. This can be done using a system reset or data re-initialization. Here are 3 scenarios where the non-destructive effects can be found. This is defined as the change of state in an electronic device (chips, transistors, microprocessors) by the passage of an energetic particle striking a sensitive node of the circuit. Moreover, in the logic circuits, SEU occurs when a SET propagates through a combination logic, and it is generally captured by a flip-flop [12]. SEFI happens when the device stops normal functions, and this requires a power reset to resume normal operations. It is a single event with a complex failure that can usually cause ICs to lose their operating principle for short time. Moreover, it has been found that complex devices suffer the most SFIs [3].

2.2.4.2 Destructive Effects

Even though the effects of the single events occur for a short time, some can result in catastrophic failure of the electronic device. The other effects may reduce the performance capabilities to the point that it stops working within the operating tolerances of the circuit. These effects are known as destructive SEE. Their common types include single event latch-up (SEL), single event burnout (SEB), single event gate rupture also known as dielectric rupture (SEGR/SEDR), and single event snapback (SES) [12]. This event is often stimulated in ICs by a pn-pn 4-layer structure when a charged particle track turns on a parasitic transistor. This is clearly shown in Figures 4 a and b where the latch-up feedback is observed between the VDD and VSS of the 2 transistors. Furthermore, the feedback will continue until the power source is removed or the device is destroyed [3], [8], [12].

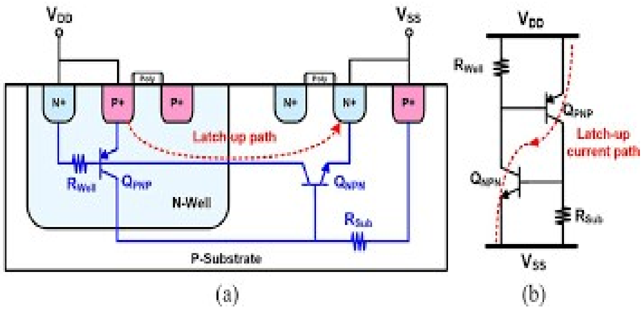

Figure 4: SEL occurs when a parasitic transistor connects 2 adjacent nodes through the substrate [12].

SEL harms CMOS circuits with NMOS and PMOS transistors (n-p-n and p-n-p thyristor). If the thyristor is irradiated, the product of both transistors' current gains will surpass 1 (npn pnp > 1), causing a latch-up [9]. Heavy ions striking a semiconductor cause avalanche multiplication. If the event persists, the current pulse's amplitude will boost and the transistor will mistakenly cause ON, causing irreparable damage to the electrical device [12]. This can cause a short circuit between drain and the gate, causing permanent gate damage. Fig.4 shows a block diagram showing single-event effects.

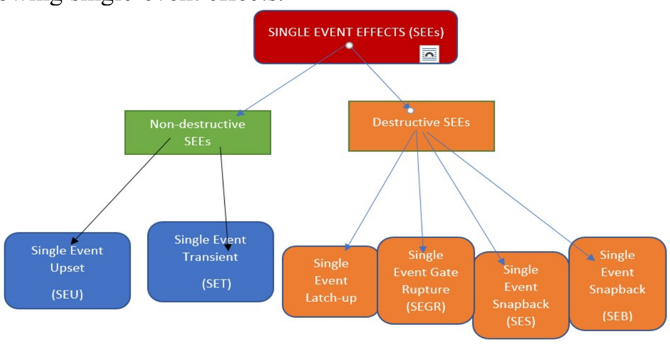

Figure 4: Summary of single event radiation effects

3.0 RECENT HARDENING TECHNIQUES

The term "Radiation hardening" refers to the process of making electronic components and circuits (ICs) more resistant to the damage resulting from ionization radiation levels from the environment. There are several hardening techniques, and they are classified into Physical radiation and Logical radiation hardening techniques [4].

3.1 Physical Radiation Hardening Technique

Generally, ICs and other electronic chips can be physically hardened by increasing the resistance of the design during manufacturing (on device and circuit level design) [3]. It was found that the device size (for instance on the gate) can be enraged to improve the radiation tolerance. Moreover, the Guard rings can also be applied to different circuits to avoid SEL and inter-device leakage. Generally, physical radiation techniques operate on different physical means and some of the explained methods in this chapter include insulating substrates and bandgap semiconductors, using bipolar ICs, acquiring radiation-tolerant SRAM, and so forth [4].*3.1.1. Insulating Substrates and wide bandgap semiconductors*

Silicon on Insulator (SOI) and Silicon on Sapphire (SOS) are common insulating substrates used in physical radiation methods, especially on chips [4]. SIO is a semiconductor wafer technology that uses less power than ordinary bulk silicon. SOI involves generating a thin insulating layer between a thin silicon layer and a silicon substrate. Insulator supports silicon junction. 15% more efficient than bulk CMOS. Fourteen Compared to CMOS, SOI uses 20% less power. Alumina on Silicon on Sapphire (SOS) technology uses a thin silicon layer on a sapphire aluminum oxide (Al203) wafer to make MOS ICs. It employs SOI CMOS technology. SOS prevents stray radiation currents. SOS is flawed. Sapphire substrates Designing tiny transistors for high-density commercial applications is tough [4]. GaN and SiC power extreme electronics. Efficient and EM-friendly GaN power devices. Wide-bandgap substrates are employed in high-radiation areas such as satellites, data transmission, drones, robots, and spacecraft [4].

3.1.2.Bipolar Integrated Circuits

Bipolar ICs are made of BJTs (BJT). BJTs are electronic devices having 3 terminals (Base, Emitter, Collector) made by doping semiconductor material and used for amplifying and switching. Bipolar ICs offer a better radiation tolerance than CMOS circuits, withstanding up to 1000 krad [4]. Bipolar technology permits many ICs to be manufactured, even in extreme environments, because of its robust gate dielectric and high mobility [14].

These ICs are primarily made of wide bandgap semiconductors used in High Voltage (HV) switches and rectifiers. Silicon carbide (SiC) and Gallium nitride (GaN) are popular wide semiconductors for high-temperature and high-radiation situations [15].

3.1.3.Radiation tolerant SRAM

Technically, Radiation tolerant SRAM consists of the 2 inverters with input and output where the resistors are connected between the output of the first inverter and the input of the second inverter connected from the supply (VDD) and ground (VSS) as shown in figure 5 [16]. The 2 cross-coupled inverters are made of four Metal-Oxide-Semiconductor Field-Effect Transistors (MOSFETs) denoted as (P1, P2, N1, N2). The additional two MOSFETs also known as access transistors noted as (N1a and N2a) serve to control the access to a storage cell during the writing and read operations. Furthermore, those access transistors are connected and controlled by the world line, and they decide which cell will be connected to the bit lines [16].

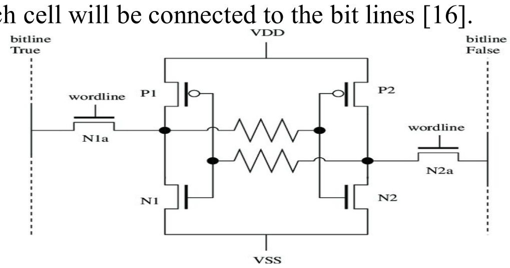

Figure 5: Simple figure showing the operation of SRAM [16].

Adding a large value resistor is used to overcome the radiation effects on SRAM inside Field Programmable Gate Array (FPGA) [4] . SRAM cells have also been designed for commercial applications including total ionizing dose (TID) hardness. [17], [18].

3.1.4. Shielding Protection

Shielding is a promising radiation strategy to reduce radiation impacts on electronic devices and ICs [3]. Radiation sources and gadget types are determined to shield. Shielding materials include air, water, soil, and materials. Concrete and steel neutral shielding requires channeling [19]. In some electronic devices, alloys (carbon) and stainless steel are used as shielding materials [20]. This costly and difficult-to-manufacture shielding method is popular in spacecraft due to its radiation tolerance [21]. The common shielding method is depleted boron [19]. Depleted boron is utilized to manufacture chip-protecting borosilicate glass layers [4].

3.2 Logical Radiation Hardening Techniques

Several software topologies have been created to avoid radiation effects especially SEEs. For instance, [22] demonstrates a Radiation Hardening Software (RHS) project that focuses on both temporary and permanent memory failures in memory chips and processor caches. The required logic methods for such different software hardening techniques include error-correcting memory, redundant elements, and watchdog timer which are explained next [4].

3.2.1 Error-Correcting Memory

Some chips particularly Dynamic Random Access Memory (DRAM) are protected against errors by adopting Error-correcting code memory (ECCM) which is also known as Error Detection and Correction (EDAC) is adopted in ICs and chips from servers [4] , [23] . EDAC is popularly applied in designing an On-Board Data Handling (OBDH) to support the satellite's subsystem in managing and correcting errors. OBDH is programmed using Real-Time Operating System (RTOS) [23] . Radiation effects usually harm the memory content and therefore, a scrubber circuit is employed to sweep the memory by reducing and preventing the accumulation of errors [3], [4], [24]. Generally, preventive, and corrective scrubber circuits are common scrubbing types and they both follow 3 main steps [4].

3.2.2 Redundant elements

Redundancy is one of the techniques that ensure the tolerance against faults induced by radiations to electronic circuits, especially ICs and Chips [4], [25]. They are used to build circuits that tolerate radiation effects in space either in hardware or software circuits from several space applications to enhance high reliability [25] . At the circuit level, one bit is replaced with 3 bits, and separate voting logic for each bit to continuously determine its results [4]. Recently, the Triple Modular Redundancy (TMR) technique has been implemented to provide the full single fault-masking with a more than 200% of power and area of overhead cost [25] [26].

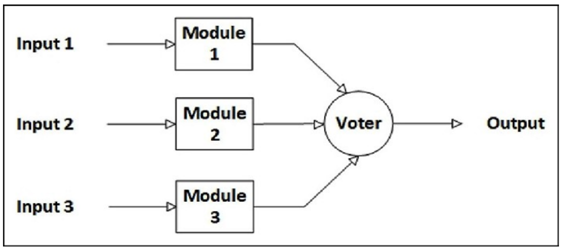

Figure 6: Diagram showing the operation of a triple modular redundancy (TMR) [26].

3.2.3. Watchdog Timers

They are popularly used in computer systems to facilitate automatic correlation of temporary hardware faults and avoid software errors from a disturbed circuit operation particularly those with severe effects of radiation [27]. The single-stage watchdog timer (shown in figure 7. a) comprises a single timer stage that resets the Central Processing Unit (CPU). While a multistage watchdog timer is made up of 2 or more timers cascaded together where each timer is known as a timer stage as shown in figure 7.b.

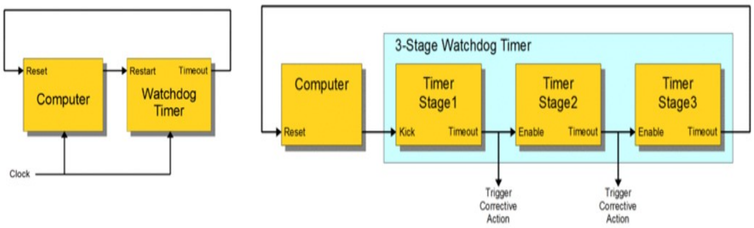

Figure 7: Single and multi-stage watchdog **[27]**

When the fault occurs, the computer system kicks the watchdog timer and the computer always detects the system whether is functioning and it will only kick the timer if all fault detection has passed. Soft faults that mostly result from software bugs, electromagnetic interference (EMI), and transients (which are caused by radiation events to logical circuits) can always be treated by using watchdog timer circuits [28].

4.0 Conclusions

Radiation from space and powerful nuclear reactors affects electronic components severely, but earth-made components also include faults that degrade their function. ICs are made of semiconductors, which would die without radiation protection. These effects modify the devices' functioning and performance, although the damage depends on radiation type, energy, flux, and exposure length. Alpha and beta particles are direct ionizing radiation, while gamma rays and neutron radiation are indirect. They damage silicon semiconductors, which make up most terrestrial electronic components like transistors. Most electronic semiconductor components (ICs) are sensitive to radiation. Different particle energies contribute differentially to ionization and displacement damage. Radiation effects on semiconductors and integrated circuits are key to studying radiation effects and repercussions. The process of making them more resistant to radiation damage is called radiation hardening. Radiation hardening involves designing and manufacturing radiation-tolerant electronics and systems. IC, sensor, and military aerospace manufacturers used hardening procedures to assure proper operation. Bipolar and bulk silicon radiation causes ionization and displacement. Findings highlighted that modern SRAM cells seem to have radiation tolerance properties where they can withstand up to 300 krad which makes it more popular in on-detector readout electronics including The Large Hadron Collider beauty (LHCb) Outer Tracker experiment This portion discusses the effects of displacement damage and ionization on bipolar transistor characteristics. Radiation-induced defects and modifications in devices, defect behavior, including charge state effects, defect mobility, and ionization-enhanced annealing will be discussed.

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