The Study of Radiation Effects on Electronics in Space Environments

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Abstract- *Due to the presence of Radiation, Space is the challenging environment for the electronic devices to perform. The performance of semiconductor devices is degraded by these radiations. The damage is caused in most of the semiconductor circuitry. The effects of these damages are categorised into Displacement Damage, Ionizing Effects and Single Event Effects. This paper deals with the study of the sources of radiation and their effects on the semiconductor devices.*

Keywords- Cosmic Rays, Ionization, Radiation Effects, SEE, Van Allen Belts.

I. INTRODUCTION

The presence of Radiations makes the space harsh environment for the electronic devices. Most of the electronic circuitry is susceptible to the damage caused by the radiation. Thus due to these damaging radiations, the electronic circuits and systems operating in space do not perform up to their designed specifications. The radiation environment speeds up the process of ageing in these circuits. The Natural Space Environment consists of the charged particles trapped in the Radiation Belts, protons and a very small amount of the heavy nuclei produced by the solar events. The prime ionizing source in electronics is the Cosmic Rays, which are produced in the supernovas in our galaxy or in any other galaxy. [1]

The amount of energy involved in the ionization process is given by the LinearEnergy Transfer (LET) Function. The common unit of measurement of this ionization energy is the rad, however the SI Unit for the same is gray. 1 gray is equivalent to 100 rad.

II. SOURCES OF RADIATION

The sources of radiations in the space are categorised into:

Cosmic Rays: Cosmic Rays are everywhere in the space. A typical cosmic ray beam consists of 85% protons, 14% alpha particles, and 1% heavy ions together with the X-Ray and the Gamma Radiation. The cosmic rays which have energies ranging from 10^8 to $2x10^{10}$ eV have severe effects on the electronic circuitry. Cosmic Rays are not the concern for terrestrial operating systems, as the atmosphere filters most of these. Cosmic Rays generally cause Soft Errors.[5]

Radiation Belts: The layer of charged particles surrounding a magnetized planet is called the Radiation Belt. The Earths Radiation Belt is referred to as Van Allen Belts in the honour of its discoverer James Van Allen. Most particles that comprise the radiation belt come from Solar Flares and the other galactic phenomenon.

Solar Winds: Solar Winds mainly consist of protons, electrons and alpha particles having energies between 1.5 to 10 keV. It is the plasma stream released from the upper atmosphere of the sun. This wind has varying density, temperature and speed over time and over solar longitude. Due to their high energy, they escape the Sun’s Gravity.[3]

Coronal Mass Ejection: The Coronal Mass Ejection is the burst of gas and magnetic field in the solar wind. It mainly arises from the solar corona. A typical CME consists of: low electron density cavity, a dense core and a bright leading edge. Most electrons originate from the active regions of the sun’s surface. CME reach the velocities between 20 to 3200 km/s.

Solar Particle Event: When the particles emitted by the sun get accelerated towards the sun itself in the solar flares or to the interplanetary space by CME shocks, the events are referred to as Solar Particle Events or Proton Storms. These are hazard for the space electronics.

III. EFFECTS OF RADIATION

The effects that are caused by the radiations in electronic circuits and systems are grouped as:

Ionization: It is the damage caused by the radiation on the semiconductor lattice during the exposure. Ionization causes the slow and gradual degradation of the performance of devices.

The incident radiation enters the semiconductor like silicon and creates the Electron-Hole Pair (EHP), if the radiation has sufficient energy to move the electron in the valence band to the conduction band across the materials band gap. Thus when the Electron Hole Pairs are created, the electrons and the holes are free to move under the influence of the electrical field (if any). The electrons are swept much readily due to their high mobility. A small fraction may undergo recombination or get trapped.

In the CMOS devices, the Electron Hole Pairs are created in the gate oxide layer due to the radiations. Figure 1 shows the effect of the radiation on the gate oxide of the N-Channel MOSFET. Figure 1 (a) shows the normal operation of the MOSFET, while as Figure 1 (b) shows the post radiation effects. As a result of the radiation exposure, the positive charged particles are trapped in the field oxide layer which produce negative threshold voltage shift.

The transistors are quickly separated by the electric field within the space charge region, as a result of the radiation exposure. The electrons having high mobility drift rapidly while the lower-mobility holes drift slowly in the opposite direction. Due to the imperfections in the crystals, the slow moving holes may get trapped. The formation of Dangling Bonds at the oxide-bulk interface can also lead to the traps. Some of EHPs recombine creating the currents, also the trapped holes in the crystal imperfections influence the threshold voltage of the transistor. [1]

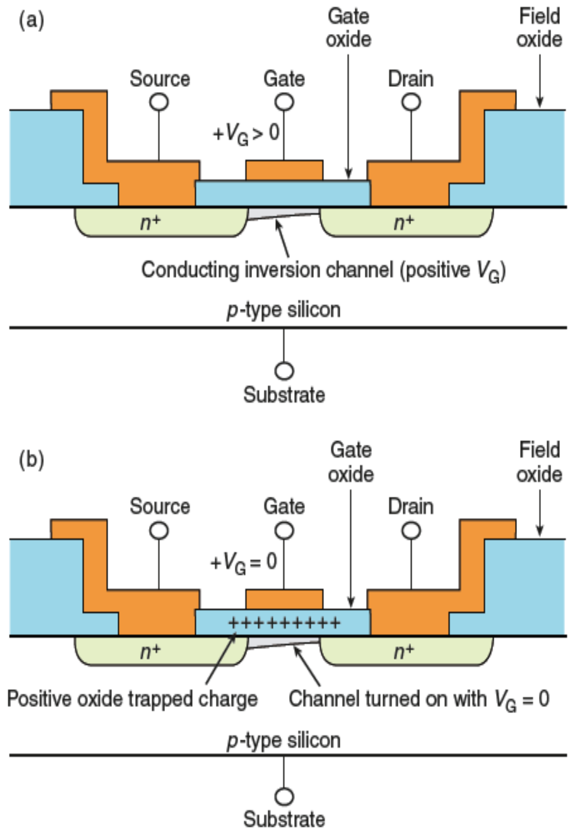

Figure 1 Schematic of N-Channel MOSFET showing the effect of radiation on gate oxide layer. Normal Operation (a) and after radiation exposure (b). (Adapted from Ref. 1)

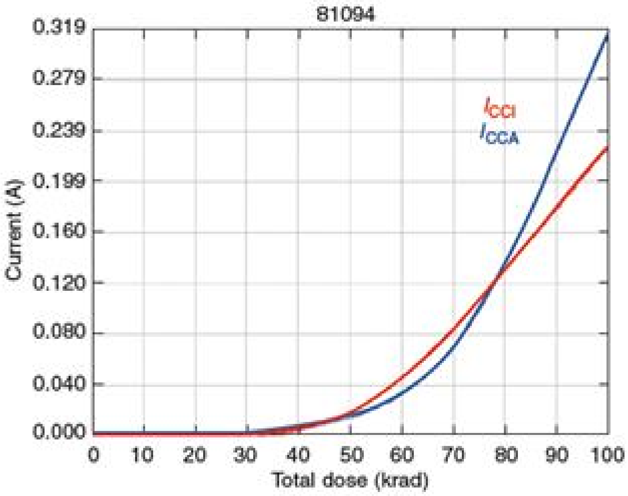

Figure 2 Supply current versus TID for an Actel RTSX72SU FPGA. (Adapted from Ref. 2.)

The Digital devices are affected by the ionizing radiation because the trapped charges may shift the MOS threshold levels and timing margins get degraded. In the case of high damage, the device may cease to perform.

The short-time, high-intensity pulse of radiation causes the photocurrents in the entire body of the semiconductor. This is the case of transient damage. Its effects include changing the logic state of flip-flops and other registers. It causes temporary problems to the devices. Howeverpermanent damage may occur if the duration is too long.

Displacement Defects: The Lattice Displacement or the Displacement Damage is mainly caused by the neutrons, protons, alpha particles, heavy ions and very high energy Gamma Photons. Displacement Damage is shown by the devices that depend on the bulk physics for their operational characteristics. The devices in this category include solar cells, particle detectors, electro-optic components and even some linear regulators. In the Displacement Damage of the semiconductors, the crystal or lattice structure gets changed, thus affecting the fundamental properties of the material. The displacement damage causes an increase in the number of the recombination centres, depletes the minority charge carriers and worsens the analog properties of the affected junctions. As the bipolar devices are dependent on the minority charge carriers, they are worst hit by the displacement damage. As far as the output is concerned, due the displacement damage, we get increased noise in the output and consequent decreased energy resolution.

The incident particle type, the incident particle energy and the target material are the parameters upon which the displacement damage depends.

Non-Ionizing Energy Loss (NIEL) is the most common method to quantify the displacement damage.

Single Event Effects (SEE): Single Event Effects are the phenomenon mostly associated with the digital devices. SEE is initiated if the charge accumulated or collected at the junction exceeds its threshold. SEE can be destructive or non-destructive. Destructive effects result in device failures, whereas non-destructive ones cause loss or corruption of data.
The basic mechanism by which the SEE are generated is that when a charged particle travels through a device and loses its energy in the material, SEE occurs. A highly localized effect may be caused similar to the one in transient dose effects, which results in the bit reversal, a destructive latch-up or a burnout. A circuit level effect is caused by the charge collected due to the striking of the single charged particle on the semiconductor. The stopping power of the incident particle in the target material determines the number of electron pairs generated. The charge collection threshold for the single event is called critical charge. SEE rate gets increased with the decreasing critical charge for the device. The particle will deposit double energy, if it strikes at 600 angle, as compared to the normal incidence.

Latch-up: If the single particle interaction induces the high current state in the electronic devices, latch-up is said to have occurred. In the CMOS ICs due to the closely fabricated structures, the parasitic bipolar transistors are formed from the ICs n-channel and p-channel transistors. The collector of each parasitic bipolar transistor is connected to the base of another transistor forming the positive feedback.

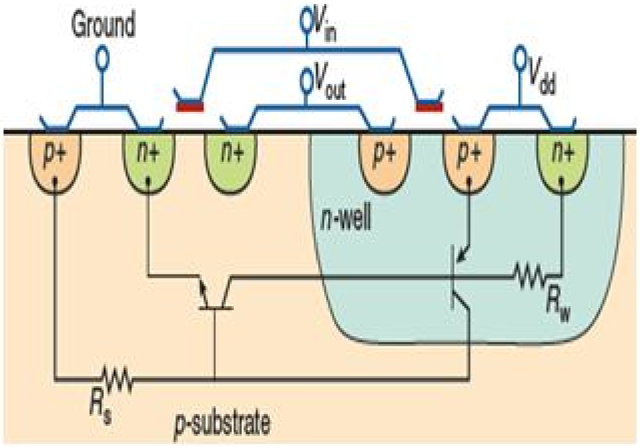

Figure 3 SCR like structure formed in bulk CMOS Inverter. (Adapted from Ref. 7)

This circuit is equivalent to a four layered device, Silicon Controlled Rectifier. The current does not flow in the parasitic base regions under normal conditions. However if a small current is injected in the parasitic base region, large current is established quickly due to the positive feedback. This current continues to flow between the IC power supply pins until the voltage falls below the threshold. This sustained high current state is called Single Event Latch-up (SEL). The latched part may be permanently damaged due to thermal runaway.[6]

Damage to the Power MOSFETs: The power MOSFETs are sensitive to other SEE mechanisms like **Single Event Burnout (SEB)** and Single Event Gate Rupture (SEGR). The Single Event Burnout (SEB) creates the high current states which leads to the functional failure of the device.The current is induced in the p-structure forward biased parasitic transistor due to striking of the charged particles. The substrate under the source region is affected and the higher drain-source voltage causes the avalanche thus high current flow.The result of this condition is the high current and local overheating.

Another damage in the power MOSFETs caused by the radiation is the **Single Event Gate Rupture (SEGR)**. It is the condition when the incident charged particles form the conducting path in the gate-oxide layer of the MOSFET. The results of this breakdown are the local overheating and ultimately the complete destruction of the device.

When the EEPROM cells are subjected to the operations of Write and Erase, this event can occur, as the memory cell is subjected to the high voltage.[4]

Single Event Upset (SEU): SEU is the change of the state of the bi-stable element when a single charged particle strikes it. SEU is non-destructive effect and can be corrected by the rewrite operation. Bit Flips are the common SEUs.
There are two parameters upon which the SEU vulnerability depends.

- Minimum energy required to produce upset.
- The surface area of all the sensitive nodes.

Single Event Upset (SEU) phenomenon is commonly experienced in the Static Random Access Memories (SRAM) and the Dynamic random Access Memories (DRAM).

There are many identical memory cells arranged in an array to from SRAM. It consists of four transistors and when the radiation is incident on their drains SEU is induced.

DRAM cells store data using charge stored in capacitor. So only one stage is susceptible to the damage (i.e. high level). As the storage mechanism is passive, so both cell storage errors and bit line errors occur.

Both the SRAM and the DRAM cells are associated with additional circuitry which is also vulnerable to SEUs.

Single Event Transients: When the transient current is produced by the charged particles passing nearby, there are voltage fluctuations at the node, and are called Single Event Transients (SET). The SET do not damage the device. However, the SETs can corrupt the data. It typically occurs during the heavy ion testing. Linear regulators, DC/DC converters, and the devices operating at the high clock speeds are more prone the transient damage. SETs can also produce the corrupted data at the output of the Analog-to-Digital-Converters.

Single Event Functional Interrupt (SEFI): Single Event Functional Interrupts are the SEUs when the charged particle affects the control circuitry of the system. This phenomenon causes the device to operate in an unpredictable fashion. It places the device in an unrecoverable mode. Although the device performs but not normally. It produces the data, control and interrupt errors from which the complex recovery methods are required to bring back the device to the normal operating condition.[6]

Stuck Bits: Stuck Bits are categorized in the permanent failures. It occurs when the radiation affects the bi-stable devices. The radiation changes the state of the device and also gets stuck-in permanently. The Stuck Bits are not even corrected by the Error Detection and Correction (EDAC) Codes, as they recover the system from single bit errors not from double bits ones.[8]

IV. CONCLUSION

The radiation environment in space poses a serious threat to the electronic circuitry operating in the space crafts and space missions. In this paper we dealt with the effects of these radiations. The effects like Ionizing Effects, Displacement Effects, and Single Event Effects have been discussed in detail. Further this paper paves the way for the study and the extensive research in the radiation caused damage.

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