Final

Radiation Effects on Microelectronics and Future Space Missions

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Abstract—**This paper briefly reviews the three basic radiation effect mechanisms, and how they interrupt the functionality of currently available non-volatile memory technologies. This paper also presents a very general overview of the radiation environments expected in future space exploration missions. Unfortunately, these environments will be very harsh, from a radiation standpoint, and thus a significant effort is required to develop non-volatile technologies that will meet future mission requirements.**

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1. INTRODUCTION

During the next few years, plans call for NASA to begin development on several new deep space missions, for launch in the coming decades. The team members working on these missions will be faced with some technical challenges of unprecedented complexities. The efforts to overcome some of these difficulties will overshadow any previous attempts by the space exploration community. One such difficulty that will be common to many of these missions is the prolonged exposure to radiation fields, with intensities far greater than typical NASA missions.

The presence of radiation can interfere with the operation of a spacecraft in many ways. For radiation levels of realistic space missions, the most susceptible components (discounting humans) of spacecraft are typically the semiconductor–based electronic parts. Thus, as space exploration efforts have developed, out of necessity, so has the study of the interaction between radiation and the operation of microelectronic devices.

Over the last forty years, much has been learned regarding the fundamental mechanisms relating to radiation effects on microelectronics, as well mitigation techniques. These mitigation techniques can be at the device level, such as developing device technologies that are less susceptible to the fundamental mechanisms, or at the system level, such as designing systems robust enough to tolerate the loss of integrity of a fraction of its microelectronic components. In practice, space systems are built by implementing both these philosophies to various degrees. As a testament to the success of this field of study, one only needs to look at the large number of successful space missions completed during this time period. However, as stated earlier, NASA is on the verge of making a quantum leap regarding the radiation levels that missions will need to tolerate, and thus great strides in this field will be needed for future successes.

One critical capability of any spacecraft is reliable non-volatile memory (NVM) storage. Any type of information that is critical to the operation of the spacecraft or that cannot be retrieved in case of a loss of power is required to be stored in non-volatile elements. Examples of critical system data are the boot up procedures and flight software for the avionic subsystems. An example of data that cannot be reconstructed, if lost, is science data that was taken during an earlier point in the mission. Permanent loss of either data type would be considered a mission failure.

Unfortunately, from knowledge of technologies and previous experience, it is expected that the NV variants currently available will not be capable of simultaneously meeting the radiation, reliability, and capacity requirements of the proposed missions. Thus a substantial effort to develop radiation tolerant NV technologies at both the parts and system level will be required. Section 2 of this paper reviews the fundamental mechanisms with which radiation interacts with material it passes through, as well as discusses the induced macroscopic effects when this material is an NVM unit. Section 3 gives a very brief description of the radiation environments expected for this new generation of space missions. Because the environments depend on explicit details of the missions, which are still in the very early stages of planning, not much can be definitively stated in terms of radiation levels. However, this section is meant to introduce the reader to the reasons why this class of missions would be radiation intensive.

2. NV MEMORIES & RADIATION EFFECTS

Typically, radiation induced malfunctions in microelectronics can be attributed to one of the three classical mechanisms: Total Ionizing Dose (TID), Displacement Damage (DD), or Single Event Effects (SEE). However, in some specific instances, the failure can be attributed to synergistic effects between these mechanisms. Section 2.2 briefly introduces these three mechanisms; however, the curious reader is encouraged to see [1] for more information on TID and DD, and [2] for more information on SEE. Both texts provide a rigorous theoretical discussion on the respective subjects, and describe some of the more subtle nuances associated with this complex field of study. As radiation passes through a crystalline material, the medium is affected via two basic mechanisms: ionization and displacements.

2.1 FUNDAMENTAL INTERACTIONS

Ionization is the process of liberating the valence electrons from the atoms comprising the lattice. If an electron is not bound to a nucleus, it is essentially free to respond to the influence of external electromagnetic fields, and thus the effective electrical conductivity of the material is raised. In a semiconductor device, which operates on the principle that the conductivity can be controlled to great precision by the application of an external bias, the consequences can be extreme. The situation is made worse when it is realized that the liberation on a valence electron leaves a hole, and effectively results in creating another mobile, charged carrier. In the language of energy levels, a valence electron makes the transition to the conduction band (due to the energy delivered by the radiation), leaving a vacant state (a hole) in the valence band.

A displacement occurs when the penetrating particle delivers enough energy to displace an atomic nucleus from its location in the crystal lattice. If the displacement is stable, i.e. the displaced nucleus, or primary knock on atom (PKA), does not fall back to its initial lattice position, carrier generation/recombination sites are created. This affects the lifetime and equilibrium ratios of both majority and minority carriers. Again, because the operation of semiconductor devices depend upon these precisely controlled quantities, the functionality of the devices are compromised. In terms of energy levels, this creates distortions in the energy bands located not only near the PKAs initial position, but also near its new location. This creates energy levels in the band gap that increases the probability for an electron to make the transition (in either direction of) between the valence and conduction bands.

The ionization process is typically due to the direct elastic electromagnetic interaction of the penetrating particle with the atomic electrons. However, it should be noted that secondary particles can be produced via inelastic electromagnetic and hadronic interactions with the atomic nuclei. These secondary particles can also contribute to the ionization process. Thus radiation effects are the direct result of fundamental electromagnetic and nuclear physical phenomena.

2.2 MACROSCOPIC EFFECTS ON NVMs

Both TID and DD are cumulative effects, i.e. the affected operation of the device is a function of the integrated (in time) radiation environment. In contrast, the SEE influenced response of the device is a function of only the instantaneous radiation environment. Although many variations of SEEs exist, typically they are the result of ionization near a sensitive volume of the device. If enough electron/hole pairs are created and escape initial recombination, the functionality of the device can be interrupted. The ionization is created by a single particle striking the sensitive area, thus the terminology.

Many variants of SEEs exist, and most result in the momentary interruption of the device functionality, which will return to normal after the liberated mobile charge recombines, or is swept away due to external electric fields. In the context of NVM, these include single event upsets (SEU) and single event functional interrupts (SEFI).

An SEU will result in the loss of programmed information associated with the particular struck bit. To return the bit to the desired state, it only needs to be reprogrammed. However, a more permanent effect, a stuck bit, where the bit loses the ability to be programmed is a possibility. A SEFI typically occurs when the control circuitry of the device is struck, which can disrupt the functionality of the device in several ways. In some instances, the device cannot be written to, and in others, the device cannot be correctly read, although, in most instances the device can be brought back to normal operation by resetting the control circuitry, or a power cycle.

In must be noted that some potentially catastrophic events are also possible, such as single event latchup (SET). A latchup is a condition where two adjacent transistors become coupled together (via a conductive path created by the liberated charge), and form a positive feedback loop. This results in localized high current densities, which electrically stresses the part, induces excessive heating, and possibly permanent device failures.

The SEE susceptibility of the device is characterized by the concept of a cross section, which is a measure of the sensitive area of the device. For most effects, this area is a fraction of the total area associated with the device, thus only a fraction of the particles that strike the device will induce an SEE. Thus SEEs are essentially probabilistic in nature. Because the probability for a single particle strike giving rise to an SEE is independent from any other particle strike, the distribution of SEEs obey Poisson statistics.

The cross section is usually characterized as a function of the penetrating particle's linear energy transfer (LET), which is a measure of how many electron/hole pairs are created per unit length of the particle's trajectory. There exists a complex function relating the particle's mass, charge state, and kinetic energy, to the LET. This mapping is derived from the cross sections pertaining to the electromagnetic processes responsible for the ionization. Since the theory of electromagnetic interactions between particles is very mature, this function is known to great precision.

When ionization occurs in the oxides of the device, the fraction of liberated electrons (which are more mobile than the hole counterparts) which escape immediate recombination are driven out of the insulator by the relatively large external electric fields. The less mobile holes are left "trapped" within the insulating material. Most of the trapped holes eventually migrate to the oxide/silicon interface due to the influence of the external bias.

Over time this effect accumulates to produce gate and field oxides with greater and greater net positive charges on the silicon interface. This will degrade the performance of the device, and eventually lead to complete failure. This mechanism is referred to as total ionizing dose because the degradation is a function of the integrated (over the lifetime) ionizing dose the device has been exposed to. Because of the large oxide volumes associated with many non-volatile technologies, these devices are typically very susceptible to TID degradation.

The accumulation of displacement damage sites can also lead to device degradation. The measure of a single particle's ability to induce lattice displacements is termed non-ionizing energy loss (NIEL). In an attempt to make this concept meaningful for all projectile particle types and energies, the NIEL value of an impinging particle is typically normalized to the value associated to a 1 MeV incident neutron. This quantity is analogous to LET, however because of the complex dynamics of the PKAs and the cascades of secondary particles, a systematic application of the NIEL concept to quantify device degradation does not yet exist.

Because a fraction of the displacing interactions are hadronic in nature, the complexity of the underlying theory increases. Unlike electromagnetic interactions, as of yet, no single, self-consistent theory exists that is in complete agreement with the world nuclear physics database. Also, depending upon the nature of the penetrating particle (hadron vs. lepton), the nature of the particle's interactions with the surrounding medium vary.

This makes it difficult for the construction of a theory that applies to all radiation sources. For instance, the NIEL behavior of protons and neutrons differ greatly at bombarding energies below 50 MeV, even though the isospin symmetry between these two baryonic states is almost exact. Thus to determine the NIEL value associated with a penetrating particle of a given species and energy state would require a complex integration of several theories and models. It must be noted that many hadronic interaction models are phenomenological in nature, and thus give little insight into the fundamental physical mechanisms regulating the particle interactions.

Because of these reasons, the study of displacement damage is still in its infancy. The application of the NIEL concept to characterize the degradation of a device should be treated with extreme caution. It is clear that to make any significant strides in this field of study, the above theoretical considerations must be earnestly addressed by the space radiation effects community.

Fortunately, up till now, the displacement environment has been benign enough to not significantly affect NVM devices (however, this is not true of bipolar devices). Unfortunately, considering the harsher environments of the future missions this claim might no longer be true. Much effort, both experimental and theoretical will be needed to adequately answer this question for the future missions.

3. FUTURE RADIATION ENVIRONMENTS

The future missions referred to in this paper are deep space probes destined for the trapped radiation belts that encompass Jupiter and its Icy Moons. The magnetosphere of Jupiter is many times stronger than the one surrounding Earth, and thus the intensities and energies of the trapped particles (mostly protons and electrons) in the Jovian environment are much greater than those associated with the Earth's trapped belts.

The probes would be propelled via ion propulsion, which is an extremely efficient process (from an energy point of view), but also provides relatively little acceleration. This means that after launch, depending on missions design, the probe may or may not need to slowly spiral out of Earth's orbit in order to acquire the kinetic energy required to escape the planet's gravitational attraction. A spiral out trajectory would require the spacecraft to spend a significant amount of time in the Earth's trapped radiation belts before ever been at the top of the reaching the Jovian radiation environments.

It should be noted that the Earth orbiting environment is dominated by high energy protons with a contribution from electrons. The proton spectrum extends into the range of hundreds of MeV, while the electron distribution is heavily attenuated at energies above 3 MeV. The protons will significantly contribute to the TID and DD degradation, while also potentially induce various SEEs, via secondary reaction products.

In contrast, the Jovian belts are dominated by high energy electrons (up to 1 GeV). The proton distribution is similar to the Earth's distribution. The electrons and protons would significantly contribute to the TID and DD degradation. Due to the low ionization and leptonic nature of electrons, it is unlikely that they would induce any SEEs in devices of modern feature sizes, however the protons would pose an SEE risk.

In addition to these two harsh environments, the spacecraft would carry an on-board fission nuclear reactor that will power the vessel. This will introduce another complex radiation environment. The reactor will deliver neutrons and photons to the microelectronic devices. The neutrons will induce a large amount of displacement damage to the devices. Also, due to the absence of the Coulomb barrier, the neutrons are even more likely to cause SEE issues than trapped protons. The photons will contribute a significant amount of TID degradation to the devices.

It should be noted that unlike the trapped radiation belts, the reactor will be present over the entire mission, thus it is considered a constant source of radiation. To mitigate nearly all reactor radiation issues, the concepts of distance and shielding are being applied. It is proposed that the spacecraft bus and reactor will be separated by approximately 25 m, and thus a geometrical attenuation factor of approximately 650 is achieved. Also proposed is the construction of an effective shield surrounding the reactor. The geometry and materials used for the shield are still being designed.

In addition to these unique radiation environments, the typical Galactic Cosmic Ray (GCR) spectrum would be present, which consists mainly of protons and heavy ions. Also, some of the missions will be launched during the Solar Max period of the solar cycle, thus solar flares and ejections (protons and heavy ions) are a significant consideration. Both GCR and solar activity can induce large rates of SEE events.

4. CONCLUSIONS

Non-volatile memory units are a critical component to any spacecraft. Unfortunately, many of the currently available technologies are very susceptible to radiation and effects, which render their application in a space environment difficult at best. This paper briefly reviews the classical radiation effect mechanisms and how they potentially interrupt the functionality of NVM units.

This paper also presents a very general overview of the radiation environments expected in future NASA missions. These environments would be extremely harsh, from a radiation point of view, due to: (a) the significant amount of time spent in the trapped radiation belts of both Earth and Jupiter, and (b) because of the presence of an on-board nuclear fission reactor. Due to the inherent radiation susceptibility of some currently available NV technologies, this will present a major technical hurdle for these future missions. Much effort will be needed from both the device manufactures and mission design teams to mitigate this looming problem.

ACKNOWLEDGMENT

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REFERENCES

[1] G. C. Messenger and M. Ash, "The Effects of Radiation on Electronic Systems, 2nd Edition", Van Nostrand Reinhold, 1992

[2] G. C. Messenger and M. Ash, "Single Event Phenomena", Kluwer Academic Publishers, 1997

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>
>Hi all,
>
>
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>
>
>   Sincererely,
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>
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>
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> >
> > Below are the comments on your paper from NASA HQ. As soon as you
> > have
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> > -------- Original Message --------
> > Subject: Patterson paper comments
> > Date: Mon, 03 Nov 2003 14:22:30 -0500
> > From: Victoria Friedensen
> > To: Mary.B.Murrill@jpl.nasa.gov, Sandra M Dawson
> >
> > CC: Brian Kremer , Matthew Forsbacka
> >
> >

> >
> >
> > Mary Beth Murrill of JPL, Matt Forsbacka, and I have reviewed
the
> > paper
> > by Jeffrey D. Patterson, "Radiation Effects on Microelectronics
> > and
> > Future Space Missions". Most of our comments reflect suggested
> > changes
> > to the text.
> >
> > Query: Is the author/was this work funded by JIMO/Project
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> > This is an interesting and well written paper. We do note that
> > there are
> > no footnotes, references, or citations in the paper. Given the
> > relative
> > complexity of some of the information presented, a few well
chosen
> > citations would strengthen the author's conclusions.
> >
> > 1. Introduction, page 1, column 1, 1st paragraph, 1st sentence:
> > replace
> > the first sentence with: "During the next few years, plans call
> > for NASA
> > to begin development on several new deep space missions, for
> > launch in
> > the coming decades."
> >
> > 2. Introduction, page 2, column 1, top paragraph, last sentence:
> > change
> > 'will' to 'would' so that the phrase reads "...this class of
> > missions
> > would be radiation intensive." Given that the previous sentence
in
> > the
> > paragraph states that the mission is in early stages of
planning,
> > the
> > conditional tense is appropriate.
> >
> > 3. Section 3, page 3, column 2, second paragraph, 1st sentence:

> > change
> > 'will' to 'would' - "The probes would be guided..." Also, are
the
> > probes
> > to be guided by ion propulsion or propelled?
> >
> > 4. Section 3, page 3, column 2, second paragraph, 2nd sentence:
> > insert
> > the phrase 'depending on mission design', and delete the phrase
> > 'will
> > need to' and change to 'may or may not need to' thus- "This
means
> > that
> > after launch, depending on mission design, the probe may or may
> > not need
> > to slowly spiral out of Earth's orbit in order to..."
> >
> > NASA is striving to eliminate/reduce the spiral out time that
any
> > large
> > mission would have to endure.
> >
> > 5. Section 3, page 3, column 2, second paragraph, 3rd sentence:
> > Change
> > the beginning to "a spiral-out trajectory would'... "A spiral
out
> > trajectory would require the spacecraft to spend a
significant..."
> >
> > 6. Section 3, page 4, column 1, 3rd paragraph: change all
> > instances of
> > 'will' to 'would'.
> >
> > 7. Section 3, page 4, column 1, 3rd paragraph, 2nd sentence:
> > replace the
> > word 'severe' with 'complex' as the shielding is designed to
> > prevent the
> > worst exposure, but there are mission life factors to be
> > considered. We
> > note that the time the spacecraft spends radiation environment
at
> > Jupiter and during an Earth spiral out is the problem - not the
> > reactor
> > itself.
> >
> > We note that most of the fission neutrons are born at ~1.5 MeV
and
> > only
> > a very small fraction are at 15 MeV and these are a moot point

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> > since the
> > shield is specifically designed to attenuate these particles.
> >
> > 8. Section 3, page 4, column 1, 4th paragraph, 1st sentence:
> > change
> > 'will' to 'would' in the sentence.
> >
> > 9. Section 3, page 4, column 1, 4th paragraph, 2nd sentence:
> > change
> > 'some of' to 'nearly all'. There is little point in our
advancing
> > the
> > shielding and reactor design as planned if we can not mitigate
> > most of
> > the reactor radiation issues.
> >
> > 10. Section 3, page 4, column 1, 5th paragraph, 2nd sentence:
> > change
> > 'will' to 'would'.
> >
> > 11. Conclusion, page 4, column 2, last paragraph, 2nd sentence:
> > change
> > 'will' to 'would'.
> >
> > Let me know if you have any questions.
> >
> > Thanks for the opportunity to review the paper,
> > Victoria
> >
> >
> > Victoria P. Friedensen
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