Design and Analysis of Radiation Hardened by Design Non-Volatile RAM for Space Applications

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***Abstract* -** The non-volatile semiconductor memory chips such as flash memory, EEPROM, FRAM etc must be used for data storage. When operating in space, memory microcircuits are exposed to radiation, which can lead to data corruption and functional failures. When compared to other non-volatile memories MRAM is been considered as the good one used for space application to withstand against radiation effect. Therefore Magneto-resistive Random-Access Memories (MRAMs) are preferred for space and radiation-hardened electronics applications. The reason MRAM is selected is based on solid-state form factor, non-volatility, radiation hardness, modularity, reliability, scalability, fault tolerance, support for mission assurance, small size, low mass, and low power consumption. MRAMs provide higher bit storage densities. Radiation hardened MRAM design is a crucial aspect of space and defence applications where memory devices must withstand harsh radiation environments. Rad-Hard MRAM is designed and analysed for various parameters which shows the tolerance level for radiation effects. The design of MRAM memory will consider the impact of radiation on the device's electrical characteristics and performance. MRAM could operate at the temperature between −40 and +150°C which is prone to 2 types of radiation effects which are TID and SEE. The designed MRAM memory will mitigate the Single Event Effects (SEE) like Single Event Upset (SEU) and SEL (Single-Event Latch-up) and TID (Total Ionizing dose). In this work, MRAM circuit will be implemented using LTSpice and verify the basic read /write operation and delay levels as radiation induced current potentially leads to read/write failures and will verify the amount of radiation the circuit is immune to in terms of rad.

KEYWORDS -RHBD – Radiation Hardened by Design, MRAM – Magnetic Random Access Memory, MTJ – Magnetic Tunnel Junction, TID – Total Ionizing Dose, SEE –Single Event Upset.

INTRODUCTION

Non-volatile memory (NVM) or non-volatile storage is a type of memory that can retain stored information even after power is removed, making it useful for applications where power may be intermittent or unpredictable.. In contrast, volatile memory needs constant power in order to retain data. It is typically used for the task of secondary storage or long-term persistent storage. Non-volatile data storage can be categorized into electrically addressed systems (read-only memory) and mechanically addressed systems (hard disks, optical disc, magnetic tape, holographic memory). Electrically addressed semiconductor non-volatile memories can be categorized into several type such as Programmable read-only memory (PROM), EPROM, EEPROM, Flash memory, Ferroelectric RAM (FeRAM), Magnetoresistive RAM (MRAM), Phase-change memory (PCM), Resistive RAM (RRAM (ReRAM)) and so on.

In Flash memory it currently has the largest available volume among the alternatives. When operating in space, memory microcircuits are exposed to radiation, which can lead to data corruption and functional failures. FRAM, for example, has high endurance and fast write times, but is relatively expensive and has lower storage density than other types of memory. RRAM has thepotential for high density and low power consumption but is still in the early stages of development for space applications. MRAM, on the other hand, has high density and radiation tolerance, but canbe slower than other types of memory and has higher power consumption. In this project I have selected MRAM. The reason MRAM is selected is based on solid-state form factor, non- volatility, radiation hardness, modularity, reliability, scalability, fault tolerance, support for mission assurance, small size, low mass, and low power consumption. MRAMs provide higher bit storage densities. Due to its inherent radiation hardness, Magnetic Memory (MRAM) is also used for top-responsibility applications.

MRAM (Magnetoresistive Random Access Memory) is a type of non-volatile memory technology that uses magnetic properties to store data. Unlike traditional memory technologies like Dynamic RAM (DRAM) or Flash Memory, MRAM uses magnetic elements to store data, which can be read, written, and erased using magnetic fields. MRAM consists of magnetic memory cells that store information in the form of magnetic fields. Each memory cell consists of a magnetic tunnel junction, consists of two ferromagnetic layers and a dielectric layer in between. The ferromagnetic layers are usually cobalt-iron-boron, and the thin dielectric layer is usually magnesium-oxide (MgO). These sandwiched layers establish the MTJ with nanoscale dimensions. One of the ferromagnetic layers has fixed magnetic orientation and is called the reference layer or pinned layer. The other one is called the free layer, and its magnetic orientation changes according to the direction of applied switching current. When the magnetic orientation of free and fixed layers is aligned (parallel state), the resistance of MTJ is low, otherwise the MTJ is in high resistance state (anti-parallel state). MRAM provides a good read write capability so here MRAM is being consider as most promising memory technologies used in space applications.

LITERATURE REVIEW

A number of authors across the world at the international levels have worked on the proposed project work in some of the similar areas and have produced novel contributions. It also provides a wide range of information about various tools used and their results. Below here is a survey concerned with this project work.

There are different types of non-volatile memory and a comparative result [1] for the best suited NVM for the space applications among Flash memory, FeRAM,RRAM and MRAM across the TID and SEE levels for each one and provided conclusion that RRAM memory is very similar to those of FRAM and MRAM memories. At the same time, RRAM has a number of advantages compared to flash memory: it is immune to SEU and has a higher level of TID hardness. RRAM technology has a simpler, smaller cell structure and therefore more scalable than MRAM and FRAM technologies which allows designers to design devices with higher memory density. The TID level of Flash memory is 10-20Krad and SEU is 1.3 MeV*cm2/mg and

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that of FRAM TID: 50 krad SEL: 85 MeV*cm2/TID: 40 krad, SEL: 60 MeV*cm2/mg and for MRAM the TID is 50 krad and SEL: 85 MeV*cm2/mg.

The radiation effects relevant to each of the NVM memories[2] including the physics of and errors caused by total ionizing dose, displacement damage, and single event effects, with an eye toward the future role of emerging technologies in radiation environments. Emerging resistance change memory technologies such as MRAM, ReRAM, CBRAM, and PCRAM are relatively insensitive to ionizing radiation, single event effects, and displacement damage, as there is not a direct mechanism for interaction between radiation and the storage mechanism. They are having a high radiation tolerance level. The single bit upsets in highly scaled STT-MRAM bits (MTJs) and PCRAM bits which merit further investigation and provided the TID level of STT-MRAM is 10MRad and SEL is 84MeV cm2/mg.

The schematics for Magnetic Tunnel Junction-Magnetoresistive Random Access Memory (MTJ-MRAM)[3] are designed and simulations are carried out in 45 and 90 nm Complementary Metal-Oxide Semiconductor (CMOS) Very Large Scale Integration (VLSI) technology using analog design environment. Other memory circuits like volatile Static Random Access Memory (SRAM) and non-volatile flash memory are designed and behavioural waveforms verified. The output behavioural characteristics of MTJ-MRAM are compared with that of SRAM and flash memory. The attributes like power and delay are calculated and compared with SRAM and flash memory circuits. The study was carried out in order to integrate the non- volatile memory with field-programmable gate array (FPGA) architecture and design a non-volatile memory-based FPGA. MTJ-MRAM shows better performance than volatile SRAM and non-volatile flash memory in terms of power and delay parameters.

The 1T1MTJ cell counfiguration is developed and anaysed for radiation effect by designing a sense circuit.[4] STT- RAM is a fast, scalable and non-volatile memory technology and the cell itself is immune to high energy particles, its sensing circuit might be severely affected by radiation. The sense circuit is implemented in 45 nm CMOS technology. Simulation results show that the proposed circuit is immune to radiation pulses up to 400 Krad. This [4] robust proposed circuit can be used in the future to design more advanced memory technologies for space applications and other situations where rad-hard circuit operation is critical.

By analysing the radiation effects including SEUs and DNUs,[5] and they have proposed the radiation-hardening techniques for the SOT-MRAM peripheral read/write circuitry. The hardening write circuit is immune to NVSEUs; meanwhile, the proposed hardening read circuit can address the errors induced by SEUs and DNUs. Transient simulation is performed to validate the radiation tolerance of the proposed SOT-MRAM peripheral read/write circuitry in 65nm CMOS technology kit.

The effects of radiation induced soft errors on MRAM-based FPGAs (MFPGA) can taken into account[6]. In case of SRAM based FPGAs which usually suffer from high standby powerconsumption and also volatility so Magnetic based FPGA is an alternative replacement.Soft error tolerance of MFPGA structure is proposed. STT-MRAM based FPGAs can suggest some advantages of non-volatility, almost zero leakage power and high-performance computing. It is shown that, the proposed non-volatile, low power and high speed MFPGA is highly robust against radiation induced soft errors. The MFPGA offering a high radiation robustness does not incur a considerable design overhead comparing with the other similar MFPGAs. Basic [6] MRAM with PSCA circuit is designed and analysed later taken forward to design a radiation hardened MRAM circuit and analysed for radiation effects with waveforms.

Spin Transfer Torque Magnetic Memory by considered as one of the most promising memories for high reliability applications.[7] This is due to its intrinsic hardness to radiation, as storage is based on the spin direction of electrons instead of the charge. Here the sensing circuit with low area overhead and negligible performance degradation is designed for radhard applications. A novel rad-hard STT-MTJ sensing circuit design that decreases significantly the SEU probability of the MTJ cells is given. By using an accurate physics-based MTJ Spice model and a commercial 40 nm CMOS bulk design kit, transient and Monte-Carlo simulations have been performed to quantify the effect of charged particles strike and evaluate the performance of the proposed design. The results showed that the rad-hard STT- MTJ structure is quite robust against radiation effect with low area overhead and modest degradation in performance. The SEU probability is as low as 0.01% for more than 50 fC of injected charge.

The Hardening techniques to mitigate SEE are presented in this paper [8]. A new design of Radhard MRAM latch is firstly presented. By using 65nm design kit and an MRAM compact model, hybrid simulations have been done to demonstrate the radiation hardness. It analyzed various Radiation Hardening by Design (RHBD) techniques and proposed a new design of Radhard MRAM storage element whose behavior is quite similar to DICE type latch and could therefore replace it in conventional Radhard designs. By using 65nm design kit and an MRAM compact model, hybrid simulations have been done to demonstrate the radiation hardness. By this work it opens the door of better MRAM integration for aerospace and avionic electronics, which could become the mainstream solution in the future.

Radiation effects on MRAM such as SEL and TID tests are analysed[9]. MRAM structure and working are descried and showed the different types of radiation effect that affect thememory when used in high level applications. Reported on SEL and TID tests of a Magnetoresistive Random Access Memory. MRAM devices withstand the effect of TID up to 60 krad(Si) with only a few read errors. The dynamic in-situ configuration provides the worst-case condition. MRAM tested under dynamic sequence starts having read errors at 5O krad(Si). After 120 hours annealing at 25 degree C, three out five parts recovered and functioned normally. After 30 days, all had recovered and could be reprogrammed with new data. So MRAms are tolerable for high radiation effects.

MRAM buffer for military application to withstand any radiation caused due to harsh particles in the environment.[10] The development of new MRAM components, that use the SSDT cell and memory architecture that is presented in this paper, will eliminate the problems of volatility in main memory, buffer, and embedded applications that require small, high speed, low power, random access memory devices. In addition, with its inherent resistance to radiation effects, it has many applications in radiation environments. Initially device with size of 1kbyte was developed. A small buffer MRAM were incorporated in PLDs which provide them high speed storage.

Magnetoresistive Random Access Memory

MRAM (Magnetoresistive Random Access Memory) is a type of non-volatile memory technology that uses magnetic properties to store data. Unlike traditional memory technologies like Dynamic RAM (DRAM) or Flash Memory, MRAM uses magnetic elements to store data, which can be read, written, and erased using magnetic fields. MRAM consists of magnetic memory cells that store information in the form of magnetic fields. Each memory cell consists of a magnetic tunnel junction, consists of two ferromagnetic layers and a dielectric layer in between. The ferromagnetic layers are usually cobalt-iron-boron, and the thin dielectric layer is usually magnesium-oxide (MgO).

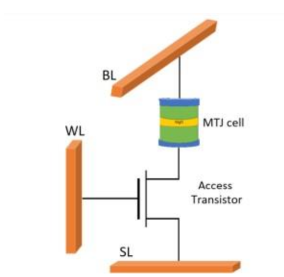

Figure 1: MRAM cell architecture

These sandwiched layers establish the MTJ with nanoscale dimensions. One of the ferromagnetic layers has fixed magnetic orientation and is called the reference layer or pinned layer. The other one is called the free layer, and its magnetic orientation changes according to the direction of applied switching current. When the magnetic orientation of free and fixed layers is aligned (parallel state), the resistance of MTJ is low, otherwise the MTJ isin high resistance state (anti-parallel state).

Radiation Effects observed in MRAM:-

Radiation effects on electronics are normally divided into 3 different categories according to their effect on the electronic components:

Total ionizing dose: Total Ionizing Dose (TID) effects on modern integrated circuits cause the threshold voltage of MOS transistors to change because of trapped charges in the silicon dioxide gate insulator. For sub-micron devices these trapped charges can potentially "escape" by tunnelling effects. Leakage currents are also generated at the edge of (N)MOS transistors and potentially between neighbour N-type diffusions. For example, TID for satellite missions can be on the order of tens to hundreds of krad, with a strong dependence on the orbit location. Details of radiation environments can be found in reviews. TID affects the state of charge storage devices by altering the charge levels stored in the cell. Modern sub- micro technologies tend to be more resistant to total dose effects than older technologies. High performance analog devices may though potentially be affected at quite low doses. Total dose is measured in Rad or Gray (1 Gray = 100 Rad.)

Displacement damage: Displacement damage refers to the phenomenon where hadrons (such as protons or heavy ions) displace atoms within the silicon lattice of active devices, leading to potential disruptions in their functionality. This effect is named "displacement" because the displaced atoms can cause changes in the material's structure and properties. CMOS integrated circuits are normally not considered to suffer degradation by displacement damage. The total effect of different types of hadrons at different energies are normalized to 1 Mev Neutrons using the NIEL (Non Ionizing Energy Loss) equivalent.

Single event effects: Single Event Effects (SEE) refer to the fact that it is not a cumulative effect, sbut an effect related to single individual interactions in the silicon. Highly ionizing particles can directly deposit enough charge locally in the silicon to disturb the function of electronic circuits. Energetic Hadrons (> ~20Mev) can by nuclear interactions within the component itself generate recoils that also deposits sufficient charge locally to disturb the correct function. The different SEE effects are normally characterized by an energy threshold and a sensitivity cross-section at energies well above the threshold.

Single event upset: The deposited charge is sufficient to flip the value of a digital signal. Single Event Upsets (SEU) normally refer to bit flips in memory circuits (RAM, Latch, flip-flop) but may also in some rare cases directly affect digital signals in logic circuits.

Single event latchup: Bulk CMOS technologies (not Silicon On Insulator) have parasitic bipolar transistors that can be triggered by a locally deposited charge to generate a kind of short circuit between the power supply and ground. CMOS processes are made to prevent this to occur under normal operating conditions but a local charge deposition from a traversing particle may potentially trigger this effect. Single event latchup may be limited to a small local region or may propagate to affect large parts of the chip. The large currents caused by this short circuit effect can permanently damage components if they are not externally protected against the large, short circuit current and the related power dissipation. So in this project MRAM is designed is such a way that it is able to withstand the affect radiation effect and the circuit designed is called Radiation hardened by design MRAM.

Radiation Hardened by design MRAM :

Radiation Hardened by Design (RHBD) MRAM (Magnetic Random Access Memory) is a type of non-volatile memory technology that is designed to withstand the effects of radiation in harsh environments such as space, high altitude flights, and nuclear facilities.

RHBD MRAM employs various techniques to harden the memory cells against radiation-induced errors. For example, the memory cells are designed to be more resistant to Single Event Upset (SEU) and Single Event Latch-up (SEL) caused by high-energy particles. Additionally, RHBD MRAM is often fabricated using radiation- hardened materials and techniques to enhance its radiation tolerance.

RHBD MRAM has several advantages over other types of memory technologies in radiation-prone environments. First, RHBDMRAM is non-volatile, which means that it retains its data even in the absence of power. This makes it ideal for storing critical data that must be preserved during power outages or other types of disruptions. Second, RHBD MRAM has fast read and write times,making it suitable for high-speed applications.

Overall, RHBD MRAM is a promising technology for use in critical applications where reliability and radiation tolerance are essential.

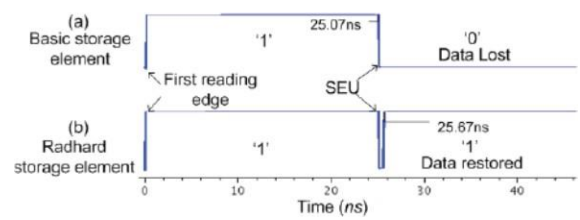

Figure 2: Effects of SEE on MRAM circuits

The SEU elimination by the Radhard MRAM is shown above. The parameters of the injected current are given in Figure 5. illustrate an example of SEU elimination, after a particle strike (at t=25ns) the correct data is restored from the non-volatile MTJs after a shortrecovery delay (~150ps). The power consumption for each restoring operation is low.

METHODOLOGY

Designing a Radiation Hardened by Design (RHBD) Magnetic Random Access Memory (MRAM) requires careful consideration of the radiation environment and the effects of radiation on the memory's performance. Here is a proposed methodology for designing a RHBD MRAM: Initially MRAM is being designed for its performance analysis and further developed to design a RHBD MRAM, MRAM technology is selected usually STT-MRAM is recommended as it is more radiation-hard than other technologies to define the radiation environment in which the memory will operate. This includes identifying the type and intensity of radiation, the expected total dose, and the expected dose rate. A RHBD MRAM designed for a low-earth orbit mission may need to withstand TID levels of up to 50 krad (Si) and SEE rates of up to 10 MeV-cm2/mg. MRAM technology is selected usually STT-MRAM is recommended as it is more radiation-hard than other technologies. The read and write circuitry (PCSA) must be designed to be immune to single event effects (SEE) and simulated using LTspice. The radiation effects are induced manually in the TCAD simulator tool and the amount that the design will withstand for the SEU and TID is calculated. In general, designing a RHBD MRAM requires careful consideration of the radiation environment, the selection of the appropriate MRAM technology, the design of the memory cells, read and write circuitry, simulations, and tools used for simulating.

CONCLUSION

In this paper various methods and analysis and comparison of different non-volatile memory for space application to withstand against the radiation effects is proposed by considering the literature review. Below table provides us with best comparison to analyse the which memory is best suited for space application to withstand against the radiation effects. By considering the above analysis we can conclude by saying that MRAM memory is best suited for this purpose. Where we can design a radiation hardened by design MRAM circuit that can withstand against TID and SEL effects by considering any CMOS technology. And this provides a future scope of taking this into a memory of large size. So from this paper MRAM can be considered and a radition level where TID = 50krad and SEL >10Mev cm2/mg can be achieved.

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