Single Event Effect Assessment of a 1-Mbit Commercial Magneto-resistive Random Access Memory (MRAM)

Philippe C. Adell, Slaven Moro, Lionel Gouyet, Christian Chatry, and Bert Vermeire

***Abstract* — Single event effect susceptibility of a 1-Mbit commercial MRAM was experimentally evaluated. The memory exhibited SEFIs when operated in a dynamic mode with an LET threshold of 2.29 MeV.cm^2/mg and a saturated cross section of 2.2x10^{-4} cm^2/device. The memory was not sensitive to SEL, SEU or MBUs.**

I. INTRODUCTION

NON Volatile Memory (NVM) technologies have key roles in modern computing systems. NVM ability to retain information while unpowered is valuable for reducing power consumption and storing critical data and/or program code for use in processor upset mitigation schemes. Magneto-resistive Random Access Memory (MRAM) is a promising NVM technology for radiation hardened applications because the storage principle is based on a configurable spin state rather than a charge state [1].

MRAM structures are comprised of layers of ferromagnetic and non-magnetic material that form a Magnetic Tunnel Junction (MTJ). The resistance of the MTJ, and therefore the logic state of the memory element, is determined by a current-controllable change in spin polarization of these layers. These materials maintain their polarization when the applied power is removed, making them ideal for nonvolatile memory (NVM) applications. MRAM presents many technology advantages such as high density, high speed, wide temperature operating range, unlimited read and write endurance and 3D integration with traditional CMOS wafers [1].

The MJT storage elements are created during backend process steps between the last two metallization layers. Figure 1 shows a cross section of the basic structure. The magnetic field of the free layer can be oriented either in the parallel or anti-parallel direction to that of the pinned layer. Parallel-programmed cells exhibit relatively less resistance than that of anti-parallel programmed cells. Experimental results have documented changes from 20% to 50% [1].

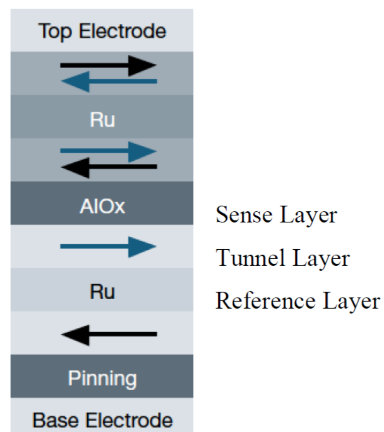

Fig 1. Top view cross-section of magnetic tunnel junction structure used to store memory bit in 1 Mbit MRAM.

During the write operation, current pulses are passed through a digit-line and a bit-line; writing only the bit at the cross point of those two lines [1]. During the read operation, the target bit's isolation transistor is turned on to bias the MTJ, and the resulting current is compared to a reference to determine if the resistance state is low or high. Figure 2 illustrates the read and write operations in a 1-transistor, 1-MTJ cell.

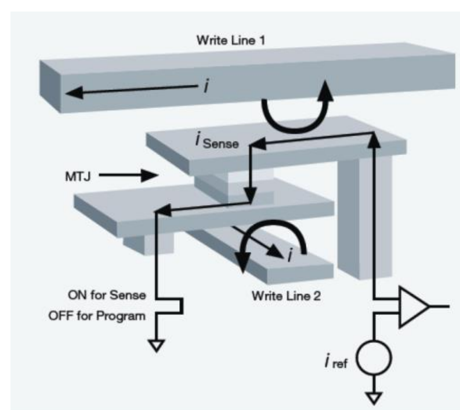

Fig 2. Illustration of read/write operation in a 1-transistor, 1-MTJ cell

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MRAM can be used in aerospace and avionic electronics applications because the spin-based storage principle of the MTJ has intrinsically high reliability, including immunity to radiation. However, the CMOS peripheral control circuitry in MRAM memory devices remains vulnerable to radiation effects. Previous MRAM radiation testing has demonstrated sensitivity to Total Ionizing Dose (TID), Single Event Latchup (SEL), Single Event Upsets (SEUs), Single Event Transients (SETs) and Single Event Functional Interrupts (SEFIs) [2-8]. A study conducted by JPL [2] indicated that a 1-Mbit MRAM from Everspin was immune to SEL but was sensitive to TID. The SEL immunity was a promising result, but other single event effects were not characterized in [2]. The objective of this paper is to complement previous work with a broader SEE assessment.

II. Part Description and Experimental Approach

This work evaluates the Everspin Technologies MR0A08B, which is a 1,048,576-bit (1-Mbit) MRAM. The MR0A08B utilizes a 1-transistor, 1-MJT bit storage element that operates in “toggle” mode [1, 2]. Toggle mode MRAM uses the same pulse sequence to write “0”s and “1”s and is not susceptible to single-line disturb phenomena, which have effects on previous MRAM technologies [1]. The device is organized as 131,072 words of 8 bits and offers SRAM compatible timing with 35 ns read/write cycles. The device operates at 3.3 V power supply.

The heavy ion SEE test campaign was completed at the Texas A&M Cyclotron facility using the 15 MeV ion cocktail. Ten parts were assessed and irradiated from the back side. Parts were accurately thinned down to 80 µm (+/- 0.5 µm). Figure 3 depicts a top view of the package marking of the MR0A08B device under test (DUT) selected for radiation evaluation. A functional test sequence was performed on each sample to check their functionality after the thinning process.

Fig 3. Package marking top view

SEE assessment of the MR0A08B was performed using a custom test system developed by TRAD (Labege, France). The test system uses a computer to control the devices through a standard IEEE-4888 communication interface. A test program logs the errors and an oscilloscope detects and captures events. The DUT test board interfaces with an FPGA board using a remote board and power supply for the DUT. For SEL characterization, three parts were tested in operating mode at maximum operating voltage (3.6 V) and high temperature (85^0C). A block diagram of the test system is shown in Figure 4 and a sample thermal image is shown in Figure 5.

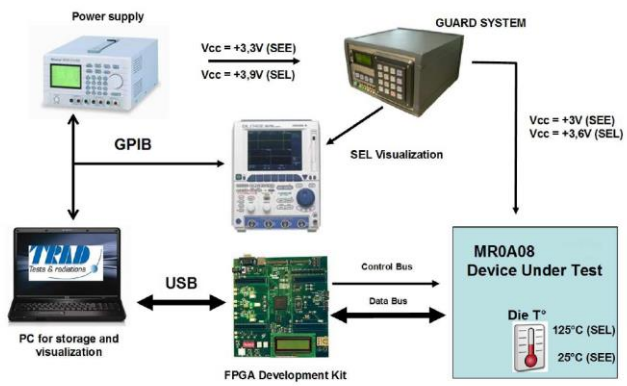

Fig 4. Test system block diagram

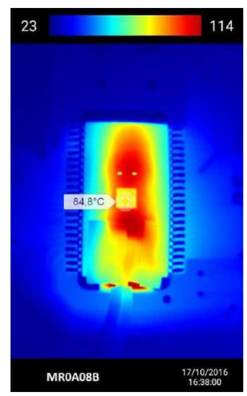

Fig 5. Thermal image of MR0A08B heated to 85 ^{0}C

The test system monitors the DUT supply current during irradiation. If the supply current exceeds the threshold current (set to 70 mA in this case), then the event is characterized as an SEL. The power supply voltage is maintained for a short “hold time” (1 ms), switched off for a specified “off time” interval (7 ms), and restored to the proper voltage level. After power is restored, the system checks for nominal current consumption and terminates the test if the current level shows signs of a destructive failure.

For SEU, MBU and SEFI characterization, the memory was evaluated for two operating modes (1) standby mode and (2) dynamic mode. In standby mode, the memory is filled with a checkerboard pattern and then exposed to heavy ions. At the end of each irradiation round, the storage is checked while the DUT is powered and again after the DUT is powered off. This mode evaluates the sensitivity of the nonvolatile memory cells separately from the on-chip control logic.

The dynamic mode test begins by initializing the DUT and the reference device with a checkerboard pattern and then verifying the correct data has been stored. The memory pattern uses “01010101” for each odd address and “10101010” for each even address. During the radiation exposure, repeated comparisons are made between the data stored in the DUT and the reference memory. Errors are logged and categorized as one for four types of errors, based on the criteria shown in Table 1.

TABLE 1. MRAM Error Type criteria

Error Type	Step 1: Read	Step 2: Delay + Read	Step 3: Write	Step 4: Read
1	FAIL	PASS	-	-
2	FAIL	FAIL (Identical to Read 1)	-	PASS
3	FAIL	FAIL (Differs from Read 1)	-	PASS
4	FAIL	FAIL	-	FAIL

If SEUs or MBUs are observed only during dynamic mode, these events are directly linked to the memory controller and are classified as SEFIs. The read data is corrupted by the controller and thus is considered as a loss of functionality. DUTs recover their functionality either by read/write or power cycles.

III. Experimental Results

Analysis was performed to verify that the heavy ions had sufficient energy levels to reach the active region of the thinned MRAM test devices. The DUTs did not exhibit any SELs, SEUs, or MBUs up to an LET of 67.97 MeV-cm^2/mg to a fluence of 1×10^7 p/cm^2.

We observed SEFIs in dynamic mode tests. The corresponding cross section versus LET results are shown in Figure 6. A Weibull Fit calculated with TRAD's OMERE tool produces an LET threshold of 2.29 MeV.cm^2/mg and a saturated cross section of 2.2×10^{-4} cm^2/device. These results suggest that a SEFI mitigation scheme is required to use these MRAM devices in a space application.

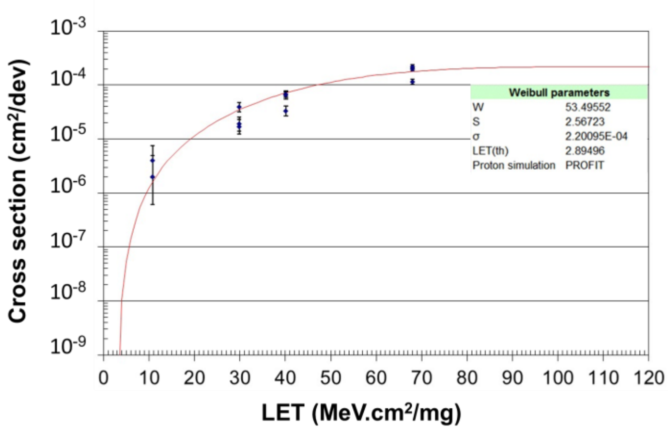

Fig. 6. SEFI cross section measured in dynamic mode. Weibull Fit was calculated using OMERE TRAD tool.

IV. Rate Calculation in Event/Day

Based on the experimental data shown in Figure 6, various SEFI rates (event/day) were extracted for different Earth orbits (LEO, MEO and GEO). Calculations were made using environmental assumptions summarized in Table II and Table III. SEFI rates and orbit information in terms of altitude and inclination are provided in Table IV. All SEFI rates were derived by using the TRAD-OMERE tools and are in units of event/day.

TABLE II. Flare Conditions

	Flare Protons	Flare Heavy Ions
Cutoff Model	Störmer	Störmer
Magnetospheric Cutoff	Vertical	Vertical
Weather Condition	Stormy	Stormy
Earth Shadow	Yes	Yes
Model	CREME96	CREME96
Flux	Worst Day	Worst Day
Lightest Element Atomic #	1	1
Heaviest Element Atomic #	1	92
Shielding Thickness	100 mils	-

TABLE III. Proton (First Section) and Galactic Cosmic Ray (Second Section) Quiet Conditions

	Protons
Geomagnetic Field Model	Jensen Cain (1996)
Model	AP8MIN
Shielding Thickness	100 mils
Atomic #	1
	Galactic Cosmic Rays
Cutoff Model	Störmer
Magnetospheric Cutoff	Vertical
Weather Condition	Quiet
Earth Shadow	Yes
Model	CREME96
Lightest Element Atomic #	1
Heaviest Element Atomic #	92

TABLE IV. Rate Calculations for Sample Earth Orbits (First Section) based on Quiet Conditions (Second Section) and Flare Conditions (Third Section)

Sample Earth Orbit (Earth Orbit Type)	Altitude [km]	Inclination [°]	Longitude
S1 (LEO)	595	90	-
S2 (MEO)	1200	90	-
S3 (GEO)	35784	0	160º W”
Quiet Conditions Rate Calculations			
Orbit	Heavy Ions [Events/Day]	Protons [Events/Day]	Total [Events/Day]
S1 (LEO)	2.9×10^{-5}	4.3×10^{-6}	3.3×10^{-5}
S2 (MEO)	3.3×10^{-5}	5.8×10^{-5}	9.1×10^{-5}
S3 (GEO)	9.6×10^{-5}	2.8×10^{-7}	9.7×10^{-5}
Flare Conditions Rate Calculations			
Orbit	Heavy Ions [Events/Day]	Protons [Events/Day]	Total [Events/Day]
S1 (LEO)	3.8×10^{-2}	4.8×10^{-4}	3.9×10^{-2}
S2 (MEO)	4.4×10^{-2}	6.1×10^{-4}	4.5×10^{-2}
S3 (GEO)	1.6×10^{-1}	2.0×10^{-3}	1.6×10^{-1}

V. Conclusion

We evaluated the SEE sensitivity of the Everspin Technologies MR0A08B MRAM. SELs, SEUs, MBUs, and SEFIs were monitored and characterized from experimental testing and 15 MeV heavy ion irradiation at the Texas A&M Cyclotron facility.

No SEL, SEU and MBUs were observed up to an LET of 67.97 MeV.cm^2/mg up to a fluence of 1×10^7 p/cm^2. SEFIs were observed in dynamic mode and have been characterized over a range of LET between 10.79 MeV.cm^2/mg and 69 MeV.cm^2/mg. A Weibull fit produces a SEFI LET threshold of 2.29 MeV.cm^2/mg and saturated cross section of $2.2\text{x}10^{-4}$ cm^2/device. SEFI rates were calculated for several Earth orbits and environment conditions.

VI. Acknowledgment

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