Radiation-Induced Soft Error Analysis of STT-MRAM: A Device to Circuit Approach

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Abstract—Spin-transfer torque magnetic random access memory (STT-MRAM) is a promising emerging memory technology due to its various advantageous features such as scalability, nonvolatility, density, endurance, and fast speed. However, the reliability of STT-MRAM is severely impacted by environmental disturbances because radiation strike on the access transistor could introduce potential write and read failures for 1T1MTJ cells. In this paper, a comprehensive approach is proposed to evaluate the radiation-induced soft errors spanning from device modeling to circuit level analysis. The simulation based on 3-D metal-oxide-semiconductor transistor modeling is first performed to capture the radiation-induced transient current pulse. Then a compact switching model of magnetic tunneling junction (MTJ) is developed to analyze the various mechanisms of STT-MRAM write failures. The probability of failure of 1T1MTJ is characterized and built as look-up-tables. This approach enables designers to consider the effect of different factors such as radiation strength, write current magnitude and duration time on soft error rate of STT-MRAM memory arrays. Meanwhile, comprehensive write and sense circuits are evaluated for bit error rate analysis under random radiation effects and transistors process variation, which is critical for performance optimization of practical STT-MRAM read and sense circuits.

Index Terms—Magnetic tunnel junction (MTJ), radiation, soft error, spin-transfer torque magnetic random access memory (STT-MRAM).

I. INTRODUCTION

THE RECENT progress on the research of emerging nonvolatile memory technology has attracted increased attentions from circuit design and architecture societies. As one promising candidate for the future universal memory technology, spin-transfer torque magnetic random access

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Fig. 1. 1T1MTJ cell structure in STT-MRAM. (a) Layout cross section view. (b) Circuit schematic view.

memory (STT-MRAM) offers a good combination of high-cell density, nanosecond access, and nonvolatility [1]. Compared to the conventional memory technologies with electrical chargebased data storage mechanism, the magnetic storage mechanism of STT-MRAM has better technology scalability and immunity to radiation-induced soft errors [2] due to its intrinsic hardness to radiation as storage is based on the spin direction of electrons instead of the charge. The applications of STT-MRAM have been successfully demonstrated in embedded memories and reconfigurable systems [3], etc.

The physical structure of magnetic tunnel junction (MTJ) is shown in Fig. 1(a) which includes an oxide barrier layer (e.g., MgO) and two ferromagnetic layers [1]. The MTJ resistance is determined by the relative magnetization directions of the two ferromagnetic layers while parallel magnetization behaviors as low-resistance state and anti-parallel magnetization behaviors as high-resistance state. Usually the magnetization direction of one ferromagnetic layer is fixed by coupling to a pinned magnetization layer and defined as reference layer while the magnetization direction of the other ferromagnetic layer can be changed by passing a polarized switching current and defined as free layer. If the switching current passes through the MTJ from reference layer to free layer, the MTJ switches to high resistance state, or MTJ switches to lowresistance state when the switching current passes through the MTJ from the opposite direction. The MTJ switching time is directly determined by the magnitude of the MTJ switching current: increasing the MTJ switching current leads to a decrease in MTJ switching time. Besides the driving ability variation of the metal-oxide-semiconductor (MOS) transistor connected to the MTJ, the thermal fluctuation is becoming

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more and more critical to affect the MTJ switching performance. Many studies have been performed to analyze the impacts of variations on the reliability of STT-MRAM operations [4]. Nigam *et al.* [5] developed a thermal noise model to evaluate the thermal fluctuations during the MTJ resistance switching process. Joshi *et al.* [6] conducted a quantitative statistical analysis on the combined impacts of both CMOS/MTJ device variations and thermal fluctuations. However, these works either do not construct a complete model to characterize all the variation types and their interactions, or require costly Monte Carlo (MC) simulations with complex macro-magnetic and SPICE models.

The popular one-transistor-one-MTJ STT-MRAM cell design is shown in Fig. 1(b). In an STT-MRAM cell, data is stored as the different resistance states of a magnetic tunneling junction (MTJ) device, in which low resistance represents "0" and high resistance represents "1." The polarization of the MTJ switching current is controlled by the voltages applied to the bit-line (BL) and the source-line (SL). The word-line (WL) is used to control the gate of the nMOS transistor and select the STT-MRAM cell. As shown in the timing diagram of write and read operation, the access transistor is turned on when read or write occurred by setting WL as high. For writing MTJ, the BL and SL is set high and low, respectively. There is a relative large current flowing through the path of MTJ and transistor. For reading the stored data in MTJ, a relative small current is applied into the path to sense the obtained voltage at node BL. Otherwise for retention mode, WL is set as low state to turn off the access transistor.

Soft error is an important factor to be considered for device reliability, especially for space electronics. Under radiation effect, when enough charge is collected, the data stored as charging state may be flipped, causing the function or data error. For STT-MRAM, the magnetic data storage mechanism makes it resilient to the radiation-induced soft errors after the data is written into the MTJ. However, the MTJ switching current is supplied by the connected nMOS transistor. If a soft error occurs at the nMOS transistor during STT-MRAM write operations, it will generate a disturbance on the MTJ switching current and hence affect the write process. To well describe the MTJ switching behavior under radiation, the transience of both MTJ magnetization switching and CMOS driving strength must be simulated together. However, the adopted access transistor in hybrid 1T1MTJ cell could be still affected by eventual radiation particles, which leads to potential threatening disturbances during MTJ switching. The reliability of STT-MRAM is degraded by the radiation particles under complicated environment as well as the intrinsic randomness during operations, i.e., thermal fluctuation [7]. Aiming to characterize the failure mechanism resulted by radiation on peripheral transistors, a compact MTJ switching model is first developed from the derivation of MTJ macro-magnetic modeling. The statistical electrical properties of the MTJ, i.e., the resistance variations, switching transience and switching time, can be simulated with the minimized run time cost. Experimental results show that our model is able to accurately simulate the write operation errors incurred by the device variations and/or the thermal fluctuations, or the intermittent switching current disturbance during the MTJ switching process in STT-MRAM designs.

Since the radiation-induced soft error is a common threat to the electrical-charged device reliability, a comprehensive cross layer analysis is performed based on the developed MTJ switching model. Although the intrinsic magnetic storage property of MTJ is immune to the radiation, the switching current of the MTJ is supplied by the MOS transistor, which is still at the risk of radiation: a soft error occurring at the MOS transistor during the write operations will cause a disturbance on the MTJ switching current. The spin-torque induced magnetization switching of the MTJ is then changed by such disturbances, leading to a delay or even a failure of write operations. However, this scenario is ignored in many researches on STT-MRAM analysis and designs. Even though several radiation-hardness memory/circuit designs techniques have been researched to improve the reliability in [8]-[12], a systematic cross-layer soft error analysis framework is still necessary to provide reasonable references. In this paper, we also comprehensively analyzed the impacts of the radiation on the robustness of STT-MRAM, e.g., a soft error occurring at the nMOS transistor, by using the proposed model. Aiming to enhance the write operation robustness of STT-MRAM cell, a comprehensive soft error analysis flow is proposed from device modeling to circuit level. First, the radiation-induced transient current pulse is obtained by performing MC simulation interaction of the particles and converting the generated electro-hole pairs into transient current pulse. The induced current pulse can be stored as look-up-table (LUT) or approximated as a double exponential function. After that, the induced current is applied into 1T1MTJ cell to obtain the probability of failure (POF) considering MTJ switching variations. For this purpose, LLG-based modeling is adopted for simulation which can capture the accurate behaviors of dynamic magnetization. The POF of 1T1MTJ cell is characterized and stored as POF LUTs, and MC simulations are performed to calculate the single event upset (SEU) rate of memory array.

This paper is organized as follows. The framework of proposed soft error analysis approach is presented in Section II. The compact MTJ switching model is provided in Section III. The modeling method of radiation-induced transient current pulse is described in Section IV. Section V demonstrates the 1T1MTJ cell soft error characterization as well as the write failure and read decision failure evaluation for practical STT-MRAM circuit designs. Section VI presents the failure in time (FIT) rate analysis on STT-MRAM memory arrays. This paper is concluded in Section VII.

II. SOFT ERROR ANALYSIS FLOW

Even though the MTJ structures are insensitive to the radiation effects among the emerging STT-MRAM, the striking particles could still affect some of the transistors inside the 1T1MTJ memory cells layout leading to the generation of electron-hole pairs inside those transistors. The generated electron-hole pairs inside the affected transistors lead to parasitic transient current pulses which can eventually disturb the MTJ switching operations.



Fig. 2. Cross layer demonstration of soft error analysis framework.

Comprehensive cross layer soft error analysis is critical for high reliable STT-MRAM design and optimization. For traditional SRAM soft error analysis, designers concerns that the stored data may be unexpectedly lost due to radiation strikes on sensitive transistors. However, the soft error induced by radiation strike of STT-MRAM is focused on the dynamic magnetization of MTJ switching process. The popular approximate R-V models of MTJ is preferred for circuit and logic simulation [13]. However, these compact models are potentially limited for the radiation-induced write failures analysis because they are unable to capture the dynamic MTJ behaviors. We choose the 1T1MTJ cell as the middle layer to characterize its soft error between physical device level and memory array circuit level.

The overall analysis flow is shown in Fig. 2 which consists of three layers: 1) device level; 2) 1T1MTJ cell level; and 3) memory array level. For device level, the main task is to model the radiation-induced transient current pulse of the access transistor under particles strike. The radiation-induced transient current pulse is obtained by performing MC simulation on the devices which are interacted with the particles strike, and the generated electro-hole pairs are converted into transient current pulse. The induced current pulse is approximated as a double exponential function [14] and built as LUT profiles for convenient access of higher level simulation. For 1T1MTJ cell level, the main task is to capture the MTJ switching failures with the effect of radiation-induced current by using physical-based switching model. The write failure characteristics of 1T1MTJ cell are also built as LUTs for different parameter configurations. For memory array level, we perform plenty of MC simulations to estimate its single event rate based on the radiation-induced current LUTs and 1T1MTJ cell write failure LUTs. For each MC simulation, a random particle is generated and the sensitive access transistors are determined by considering the memory layout (the position of each cell). Then their failure results can be obtained by querying the LUTs according to the specified radiation strength, write current magnitude and duration time. The radiation-induced current modeling is discussed in Section IV. The soft error characterizations of 1T1MTJ cell and memory arrays are described in Sections V and VI, respectively.



Fig. 3. Demonstration of MTJ magnetization.

III. COMPACT MTJ SWITCHING MODEL

In this section, we will illustrate the development process of our thermal and process variation aware compact MTJ switching model which is derived from MTJ macro-magnetic modeling.

Since the magnetization direction of the reference layer is fixed, the magnetization switching process in an MTJ can be described by the direction change of the free layer magnetization \vec{M}_f . In general, the magnetization is assumed to be a constant in magnitude. Its motion is represented by a unit direction vector $\vec{m}_f = (\vec{M}_f/M_s)$, where M_s is the saturation magnetization. At any instant of time, vector \vec{m}_f makes an angle θ with the \vec{e}_z axis while the plane of \vec{m}_f makes an angle φ with the \vec{e}_x axis as shown in Fig. 3. In other words, the motion of \vec{m}_f can be uniquely described by the coordinates (θ, φ) . The energy landscape experienced by \vec{m}_f includes uniaxial anisotropy, easy-plane anisotropy, the applied magnetic field and Langevin random field torque.

During the STT-MRAM operation of writing 1, a spin current is injected into the magnetic body along $-\vec{e}_x$ direction. We assume the spin-polarization factor is η . The spin direction is in the $\vec{e}_y - \vec{e}_z$ plane, making an angle ϕ with \vec{e}_z axis. Here, we ignore the current-generated magnetic field by assuming spin-current effect is dominant in a small magnetic body, which is the normal working condition of the MTJ in an STT-MRAM cell. The potential energy for \vec{m}_f is $U_1(\theta, \varphi) = U_K + U_p$. Here $U_K = K \sin^2 \theta$ is uniaxial anisotropy energy with $K = (1/2)\vec{m}_f H_k$ and H_k is the Stoner–Wohlfarth switching field. U_p is easy-plane anisotropy in the $\vec{e}_y - \vec{e}_z$ plane while its normal direction is \vec{e}_x axis. The environmental energy is $U_2(\theta, \varphi) = U_H + U_L$, where U_H is the applied field in the easy plane of $\vec{e}_v - \vec{e}_z$, making an angle of ψ with the easy axis \vec{e}_z . U_L is the Langevin random field related to the thermal fluctuations. The torque experienced by \vec{m}_f within the free layer under the energy landscape [15] can be written as

$$\frac{\Gamma_U}{l_m} = -\vec{m}_f \times \nabla [U_1(\theta, \varphi) + U_2(\theta, \varphi)]$$

where l_m is the thickness of free layer. The potential and environmental energy introduces the four components of \vec{m}_f . The first one is the uniaxial anisotropy as

$$\frac{\Gamma_1}{l_m K} = (2\sin\theta\cos\theta) \big[(\sin\varphi)\vec{e}_x - (\cos\varphi)\vec{e}_y \big].$$

The rest three terms are all normalized to the uniaxial anisotropy term. The normalized second term is easy-plane anisotropy as

$$\frac{\Gamma_2}{l_m K} = -2h_p \Big[(\cos\theta\sin\theta\cos\varphi)\vec{e}_y - \Big(\cos\varphi\sin\varphi\sin^2\theta\Big)\vec{e}_z \Big]$$

The normalized third term is applied magnetic field as

$$\frac{\Gamma_3}{l_m K} = 2h \begin{bmatrix} (\sin\varphi\cos\psi\sin\theta - \cos\theta\sin\psi)\vec{e}_x \\ -(\cos\varphi\cos\psi\sin\theta)\vec{e}_y \\ +(\cos\varphi\sin\theta\sin\psi)\vec{e}_z \end{bmatrix}.$$

The normalized fourth term is Langevin random field [16]

$$\frac{\Gamma_4}{l_m K} = (h_{L,z} \sin \theta \sin \varphi - h_{L,y} \cos \theta) \vec{e}_x + (h_{L,x} \cos \theta - h_{L,z} \sin \theta \cos \varphi) \vec{e}_y + (h_{L,y} \sin \theta \cos \varphi - h_{L,x} \sin \theta \sin \varphi) \vec{e}_z$$

The torque generated by the spin current can be expressed in vector form as

$$\Gamma_5 = s\vec{m}_f \times \left(\vec{m}_s \times \vec{m}_f\right)$$

where $s = (\hbar/2e)\eta J$ is the spin-angular momentum deposition per unit time [15]. Here, \hbar is Planck constant and e is elementary charge. The spin direction of the incident current is in the $\vec{e}_y - \vec{e}_z$ plane, and makes an angle ϕ with the axis \vec{e}_z . \vec{m}_s is a unit vector whose direction is that of the initial spin direction of the current. Similar to the components of \vec{m}_f , the normalized torque can be expressed as

$$\frac{\Gamma_5}{l_m K} = 2h_s \begin{cases} -(\sin\theta\cos\varphi)(\sin\theta\sin\varphi\sin\varphi\sin\phi + \cos\theta\cos\varphi)\vec{e}_x \\ + \begin{bmatrix} \cos\theta(\sin\phi\cos\theta - \cos\phi\sin\theta\sin\varphi) \\ +\sin^2\theta\cos^2\varphi\sin\phi \\ +[\sin\theta(\sin\theta\cos\phi - \sin\varphi\sin\phi\cos\theta)]\vec{e}_z \end{bmatrix} \end{cases}$$

The dynamics of \vec{m}_f can be simulated by Landau–Lifshitz–Gilbert (LLG) equation as

$$\frac{d\vec{m}_f}{dt} + \alpha \left(\vec{m}_f \times \frac{d\vec{m}_f}{dt} \right) = \frac{1}{2} \Omega_k \sum_{i=1}^{5} \left(\frac{\Gamma_i}{l_m K} \right)$$

where α is the Gilbert damping constant [17], [18]. By introducing a new time unit $\tau = (\Omega_K t/1 + \alpha^2)$, we obtain the ordinary differential equation of coordinates (θ, φ) to describe the motion of the magnetization vector as

$$\begin{bmatrix} \theta'\\ \varphi' \end{bmatrix} = \sum_{i=1}^{5} \begin{bmatrix} \theta'_i\\ \varphi'_i \end{bmatrix}$$
(1)

where the uniaxial anisotropy term is presented as

$$\begin{bmatrix} \theta'_1\\ \varphi'_1 \end{bmatrix} = -\begin{bmatrix} \alpha \sin \theta \cos \theta\\ \cos \theta \end{bmatrix}.$$
 (2)

The easy-plane anisotropy term is presented as

$$\begin{bmatrix} \theta'_2\\ \varphi'_2 \end{bmatrix} = -h_p \begin{bmatrix} (\sin\varphi + \alpha\cos\theta\cos\varphi)\sin\theta\cos\varphi\\ (\cos\varphi\cos\theta - \alpha\sin\varphi)\cos\varphi \end{bmatrix}.$$
 (3)

The applied field term is presented as

$$\begin{bmatrix} \theta'_{3} \\ \varphi'_{3} \end{bmatrix} = -h \begin{bmatrix} \cos\varphi\sin\psi + \alpha(\sin\theta\cos\psi - \cos\theta\sin\varphi\sin\psi) \\ \left((\sin\theta\cos\psi - \cos\theta\sin\varphi\sin\psi) \\ -\alpha\cos\varphi\sin\psi \right) \end{pmatrix} / \sin\theta \end{bmatrix}.$$
(4)

The Langevin random field term is presented as

$$\begin{bmatrix} \theta'_{4} \\ \varphi'_{4} \end{bmatrix} = \begin{bmatrix} \alpha(h_{L,z}\sin\theta - \cos\theta(h_{L,x}\cos\varphi + h_{L,y}\sin\varphi)) \\ +(h_{L,y}\cos\varphi - h_{L,x}\sin\varphi) \\ (\alpha(h_{L,x}\sin\varphi - h_{L,y}\cos\varphi) + h_{L,z}\sin\theta) \\ -\cos\theta(h_{L,x}\cos\varphi + h_{L,y}\sin\varphi) \end{bmatrix} (5)$$

And the effective spin torque term is presented as

$$\begin{bmatrix} \theta'_5\\ \varphi'_5 \end{bmatrix} = -h_s \begin{bmatrix} \sin\phi(\alpha\cos\varphi + \sin\varphi\cos\theta) - \cos\phi\sin\theta\\ \left((\sin\phi(\cos\varphi - \alpha\sin\varphi\cos\theta)) / \sin\theta\\ +\alpha\cos\phi \end{bmatrix} \end{bmatrix}.$$
(6)

By combining (1)–(6), we obtain an analytical model with only two ordinary differential equations to simulate the dynamic magnetization process of an MTJ over time.

As aforementioned, all four components of \vec{m}_f and the spin torque term are normalized by the Stoner–Wohlfarth uniaxial-anisotropy field H_k . For example, the easy-plane anisotropy field h_p , which is used to emulate the thin-film demagnetization field [19], [20], is defined as

$$h_p = \frac{4\pi M_s}{H_k}.$$

In our model, applied magnetic field term h is assumed to be zero. As the term representing the thermal noise in the MTJ switching, Langevin random field is affected by the environment temperature and device geometry size as [5]

$$h_{L,i} = \sqrt{\frac{2\alpha k_B T}{\gamma M_s V}} X_i(t) \quad (i = x, y, z)$$

where *T* is the environment temperature, *V* is the geometry volume of the free layer, α is the damping constant, γ is the gyro-magnetic ratio, k_B is the Boltzmann constant. $X_i(t)$ is a Gaussian random noise with zero mean and unit variance in *x*-, *y*-, and *z*-axis. And the normalized effective spin torque h_s is represented as

$$h_s = \frac{s}{l_m \vec{M}_f H_k}.$$

The definitions of all parameter are summarized in Table I and the default values are also provided for experimental configurations in this paper.

The value of θ determines the transience of MTJ resistance R_{MTJ} during the switching process as [15]

$$R_{\rm MTJ}(t) = \frac{R_0}{1 + p^2 \cos \theta(t)}$$

TABLE I PARAMETER AND VARIABLES PRESENT IN MTJ MODEL

Parameter	Description	Default Value
h_p	Easy-plane anisotropy field	180
h_L	Langevin random field	Gauss noise
h	Applied magnetic field	0
h_s	Effective spin current	$100 \ \mu A$
H_k	Uniaxial-anisotropy Field	100 Oe
α	Gilbert damping constant	0.01
M_s	Saturation magnetization	$1432 \ emu/cm^3$
η	Spin polarization factor	0.1
\dot{l}_m	Thickness of free layer	2 nm
J_c	Critical threshold current density	$9.4 \times 10^5 \ A/cm^2$
I_c	Critical current $(45nm \times 90nm)$	$30 \ \mu A$

where R_0 is the original resistance of the MTJ and p is the effective spin polarization of the ferromagnetic electrodes. The relationship between the commonly-used tunneling magnetic resistance (TMR) ratio and p is defined as

$$\mathrm{TMR} = \frac{2p^2}{1 - p^2}$$

The high (R_H) and the low (R_L) resistance state of the MTJ equal $(R_0/1 - p^2)$ and $(R_0/1 + p^2)$, respectively.

IV. RADIATION-INDUCED CURRENT MODELING

In this section, we model the radiation-induced current with the electron and hole pairs generated by the strike of high-energy particles on the metal-oxide-semiconductor field-effect-transistor (MOSFET) device [21]. Under the effect of the existing electric field between the source region and drain region, the generated electrons and holes shift into the opposite directions. This movement generates an electrical charge noise, which leads to the random transience of MTJ switching current and consequently affecting the MTJ switching performance. In this paper, the MOS transistor is implemented with PTM Low Power 45 nm technology [22] and the MTJ is assumed in a 45×90 nm elliptical shape.

A. Single Event Effect

Single event effect (SEE) [23] is induced by the interaction of the ionizing particles (such as heavy ions, protons, and neutrons) with electronic components, circuits, and systems. The state of cross section in affected devices can be determined by the transferred energy from impinging particles. The usually used metric to measure the energy deposited by the particle is the linear energy transfer (LET). If the LET of an interaction event is larger than the specified threshold LET, the particle will produce an observable effect. As shown in Fig. 4, the charge released by the impinging particle in an SEE event is collected through the so-called funneling mechanism. Most of the charge is sucked at the struck junction through a deformation of the junction potential. And the remaining charge is diffused and collected in the substrate [21].

A circuit disturbance can be only caused by a particle strike when the generated charge is collected by a sensitive node. Generally speaking, a reverse biased p-n junction is the most likely candidate to collect charge. The resulted large depletion region has a strong electric field since p side at a lower



Fig. 4. Ion track in a reverse-biased *p-n* junction [24].

potential than the *n* side. For radiation-induced soft errors of static RAM cell, transistors containing a reversed *p*-*n* junction are sensitive to particle strikes. In other words, the sensitive transistors to radiation in a memory cell are the ones which are OFF state. A particle can induce an SEU when it strikes at drain region of off-MOSFET. Since the released charge is collected at the reverse-biased drain p-n junction, the voltage at the struck node tends to decrease and turn the radiation-induced current into a voltage transient. The current decreases the potential at the drain node and possibly change the initial state if the drain potential is smaller than the cell switching voltage. The turned-off transistors are sensitive to the particles radiation because the stored data in static RAM cell has to be locked for retention when no read or write is operated. However, there is no need to lock the data stored in STT-MRAM cell due to its nonvolatile property. Hence, the turned-off access transistor is not sensitive to the radiation when no write/read operations are performed. Even though the access transistor of 1T1MTJ cell is turned on for performing write/read operations, the reverse-biased *p*-*n* junctions are still existed inside the access transistor. If the transistor is affected by a particle strike, there is still an additional current pulse generated and injected into the MTJ to disturbance its switching process.

B. Transient Current Response

SEU depends on the LET of the impinging particle, on the incidence angle θ (effective LET = LET/cos θ) and on the charge collection capability of the hit junction. The shape of the noise generated by an ionizing particle on the MTJ switching current pulse is determined by the following factors: the exact geometry of the nMOS transistor p-n junctions, the incident angle of the striking particle, and transistor doping profile, etc. In general, the shape of the radiation-induced pulse on transistor driving current can be approximated as a double exponential shape as [14]

$$I(t) = \frac{Q_{\text{coll}}}{\tau_{\alpha} - \tau_{\beta}} \left(e^{-\frac{t}{\tau_{\alpha}}} - e^{-\frac{t}{\tau_{\beta}}} \right)$$
(7)

where Q_{coll} represents the total collected electrical charge of the node in sensitive region. τ_{α} is the collection time-constant and τ_{β} is the ion-track establishment time-constant, respectively. The radiation injected current I(t) charges or discharges



Fig. 5. Resultant transient current pulse by particles strike ("NM" and "OB" represent for normal and oblique incidence, respectively).

the transistor gate and drain capacitors, generating a transient disturbance on the switching current or voltage on the MTJ. In transient analysis, a ramp approximation of the noise waveform may be used. The common approach is using a trapezoidal or triangular to model the noise generated at the electrical voltage or current outputs.

Usually the particle induced current profiles are built as LUTs by performing MC simulations for 3-D MOS device with different configurations on incidence angle, carrier density, and drain-source voltage. The effect of particles striking on particular device structures can be evaluated by using Geant4 toolkit [25] which uses MC methods to compute the number of generated electron-hole pairs due to particles strike and built as an LUTs. It requires a long runtime to obtain the practical LUTs In this paper, we adopt a typical value of carriers density for generated electron-hole pairs. Based on the LUTs of particles striking for electron-holes generation, the TCAD Altas [26] tool is adopted for SEU simulation on the specified MOS device structure to obtain the transient current characteristic. Fig. 5 demonstrates the radiation-induced transient current profiles of a 3-D nMOS device simulated by TCAD Altas for particles strike with normal or oblique incidence, various carriers density ρ and different bias voltage $V_{\rm DS}$ from drain region to source region. The current profiles indicate that particle with normal incidence results in larger transient current pulse due to the number of generated electron/hole pairs. Device with higher density carriers leads to larger current pulse, and voltage bias from drain region to source region assists to enlarge such transient current magnitude. Generally, the transient current profile is represented as double exponential model and built as LUTs. The collected charge Q_{coll} depends on the total charge collected at the sensitive node and can be calculated by integrating the current that flows at the sensitive node after the strike. Subsequently the funnel creation time and collection time is easy to be determined by fitting the current curve to double exponential model. The resultant collected charge and time constants are stored in the LUTs for convenient access.

V. 1T1MTJ CELL SOFT ERROR CHARACTERIZATION

For writing or reading each bit 1T1MTJ cell, an electrical current is applied to flow through the MTJ, but the required magnitude of current flow is significantly different for different operations. Since the existing thermal and process variation on memory cells, the resulted voltage bias from BL to SL and the access transistor size must be carefully considered to ensure the correctness of operations as well as optimizing the write driver and sense circuit design [27]. Nevertheless, the eventually radiation effect could still induce some possible soft errors during operations. The possible operation failures include write failure and read failure. A write failure could be caused by a particle strike on the access transistor while the MTJ switching is disturbed and the resulted switching delay exceeds the applied duration period. Read failure usually includes decision failure and disturbance failure. A read decision failure could be occurred if the obtained voltage exceeds the sense margin of the read circuit. And a read disturbance could be happened when the resulted read current flowing through MTJ is larger than critical current so that the MTJ state is eventually flipped. As our experimental observations, radiation-induced read disturbance failure is hardly occurred for well designed sense circuits. Hence, only the write failures and read decision failures are evaluated for 1T1MTJ soft error analysis in this paper. References [9], [10], and [12] focused on radiation hardening techniques with the respect of particles strike on transistors in sense circuit block. However, the radiation-induced SEUs should most likely occur on the access transistors of memory cells since the number of access transistor is much larger than of sense circuit block. Hence, this paper mainly focuses on the soft error analysis with the particles strike on access transistors of memory cells.

A. Write Failure

For write failure analysis, we first discuss the MTJ switching failure mechanism of 1T1MTJ with particles striking. Then the physical LLG-based switching model is evaluated and comprehensive simulation results are provided according to the implemented write circuits.

1) MTJ Switching Failure Mechanism: The cross section of the 1T1MTJ cell and the write current path is shown in Fig. 6(a). For writing 1 which indicates that free layer is flipped from P state to AP state, the ideal writing current I_{write} with no ion radiation can be obtained by

$$I_{\rm write} = \frac{Vdd}{R_{\rm DS} + R_{\rm MTJ}}$$

where *Vdd* is the power supply voltage, R_{DS} is the MOS channel resistance between drain region and source region, R_{MTJ} is the resistance of MTJ. At the onset of an ionizing radiation event, a cylindrical track of electron-hole pairs with a submicrometer radius and high-carrier concentration forms in the wake of the energetic ions passage. When the generated ionization track traverses or comes close to the depletion region, the electric field rapidly collects carriers, creating a current/voltage noise at that node. The source region is easily sensitive to the radiation due to the reverse-biased *p*-*n* junction. If particles



Fig. 6. Radiation strike on access transistor during MTJ switching. (a) Parallel to anti-parallel state. (b) Anti-parallel to parallel state.

strike the source region, it will induce a current path from source region to substrate which could be viewed as a temporary channel and its resistance is defined as R_{SB} . Using the Kirchhoff's Current Law and Kirchhoff's Voltage Law, the corresponding writing current flowing through MTJ can be obtained by

$$I'_{\rm write} = \frac{Vdd}{R_{\rm DS} + R_{\rm MTJ} \left(1 + \frac{R_{\rm DS}}{R_{\rm SB}}\right)}.$$

Thus, the writing current I'_{write} will be decreased due to the induced current I_{SB} flowing through the temporary channel from source region to substrate, that is, $I'_{\text{write}} \propto R_{\text{SB}}$. The temporary channel resistance R_{SB} is determined by the radiation strength. The stronger radiation stoked, the smaller channel resistance R_{SB} , and subsequently the smaller writing current I'_{write} which will potentially introduce significant writing failures.

Similarly for writing 1 which indicates that free layer is flipped from *AP* state to *P* state as shown in Fig. 6(b), a temporary radiation induced channel from drain region to substrate is also generated, and its resistance is defined as $R_{\rm SB}$. The corresponding writing current flowing through MTJ can be obtained by

$$I'_{\rm write} = \frac{Vdd}{R_{\rm DS} \parallel R_{\rm SB} + R_{\rm MTJ}}$$

The writing current becomes larger since the induced R_{SB} is connected with R_{DS} in parallel. This result will somewhat benefit to the writing 0 operations. However, the overall writing failures could still be determined by the introduced writing errors when writing 1 state. Hence, the degraded writing currents are taken into considerations for analyzing the writing failures of 1T1MTJ memory cell.



Fig. 7. MTJ switching transience under radiation strikes with different strength and arrival time (write current is 100 μ A and duration 5 ns).

2) MTJ Switching Model Validation: There are two factors primarily determining the impacts of a single radiation on the reliability of MOS circuitry: 1) the arrival time and 2) the radiation intensity. Fig. 7 shows the examples of the approximated undershoots of the MTJ switching current during the radiation attacks with different intensities, which is donated as negative disturbance. The corresponding MTJ resistance switching transience is also shown in Fig. 7. Following the increase of the radiation-induce switching current noise magnitude, the MTJ switching time is significantly delayed. Even though the lasting period of particle strike is significantly shorter than write current duration time, the switching behavior of MTJ could be still degraded with such negative disturbance, i.e., a worse write performance. There is no doubt if a positive current induced by particle strike could assist the switching procedure. However, such phenomenon is always occasionally happened and cannot be predicted or utilized to improve the switching performance. Hence, the negative disturbance is more preferred to be considered for evaluating the degraded write performance. Moreover, the switching time is also affected by the arrival time of radiation-induced current which should be taken into considerations for characterization.

Obviously, a radiation can affect the 1T1MTJ cell only when the incurred current noise is generated within the switching window of the MTJ. The switching window is defined as the period between the beginning and the end of MTJ magnetization damping. The magnetization angle θ represents the MTJ state which flips from 0° to 180°. As shown in Fig. 8, the MTJ switching time varies as the radiation arrival time changes. If the radiation occurs in the middle of the MTJ switching window, the overall MTJ switching time slowly increases when the attack time approaches the end of the delayed MTJ switching. This result is expected because before the MTJ switching finishes, the magnetization state is the result of an accumulated field effect where the spin-current induced torque plays the major role in driving the magnetization into the other steady state. The interruption or disturbance of this process will delay the MTJ switching time. However, if the attack occurs around



Fig. 8. MTJ switching time delayed under different write current and radiation arrival time. Write duration starts at 3 ns, and normal switching time is about 2 ns for 100 μ A.

or after the end of MTJ switching, the original MTJ switching time will not be affected.

As we can see in Fig. 8, the MTJ switching time goes back to its normal level in this scenario. Also, the increase of MTJ switching current results in a shorter switching process during which the impact of a strike is minimized. The noise on the spin-current induced torque has a relatively smaller impact (of delaying) on the MTJ switching time, compared to the case that the MTJ is driven by a lower switching current. For the smallest applied write current 50 μ A, the switching time delayed by radiation is more significantly and still not back to its normal level at 7.5 ns. If the write duration is defined as from 3 to 7.5 ns, a write failure will occur.

3) Write Failure Evaluation: Aiming to evaluate the practical influences of particles strike on 1T1MTJ cell, a write circuit is implemented to drive the memory data cell as shown in Fig. 9. The write enable (WE) input is driven as high for read operation while low for read operation. Using the WL to select this bit cell, WE and WL with high state is decided by the AND gate to turn on the access transistor of the 1T1MTJ cell. The write circuit adopts two stage of inverter for driving the BL and SL terminals of each bit cell to generate a current path flowing through the MTJ. Terminals BL and SL are driven as low and high, respectively, to write MTJ into AP state, or driven as high and low, respectively, for writing into P state. Since the write speed of P to AP state is usually slower than AP to P state [28], the transistor width on the Pto AP write current path can be enlarged or connected with additional MOS in parallel to enhance the write current and additionally eliminate such asymmetric behavior.

As discussed in Section IV, particles strike is usually modeled as radiation-induced current pulse for evaluation. However, simply attaching a current source into the circuit node cannot reflect the accurate behavior of the radiation effect. Because the resulted change of path current can be only captured by the radiation-generated temporary channel between sensitive region and substrate which could affect the



Fig. 9. Circuit diagram for the implementation of 1T1MTJ write operation.



Fig. 10. Waveform of write operation with a particle strike.

total effective channel resistance and then behavior as a write current change. As shown in Fig. 9, the radiation-induced temporal channel is modeled as a transistor which is connected into ground in parallel with the access transistor and controlled by an eventually applied voltage Rad. If the radiation occurs on the sensitive region of access transistor, the temporal nMOS is turned on by driving the input voltage Rad to change the path resistance and consequently vary the write current. Under such effect of channel resistance modulation, the total write current on MTJ is the sum of current through the access transistor and leakage current through temporal nMOS.

The STT-perpentidular magnetic anistrophy (PMA) MTJ compact model in SPINLIB [29] is adopted for write and read simulations in this paper. As the simulation results shown in Fig. 10, data is the input signal to be written into MTJ, where the AP state with high resistance represents storing one bit of 1 and P state with low resistance represents storing one bit of 0 accordingly. State is the signal of resulted MTJ states after performing write operations, which is represented as a logic 1 and 0, respectively. By setting enable as high state,



Fig. 11. Radiation strike on access transistor during MTJ read operation.

the BL and SL are precharged to generate a current flowing through MTJ while its direction is according to the input data value. Once the write current is larger than critical current, the MTJ will switch into a state representing the value of input data. As shown in Fig. 10, the logic 1 is written twice and the switching delay is about 5.59 ns. For writing the logic 0 at 11 ns, it requires about 3.2 ns to finish the switching process. However, a particle strikes the access transistor when performing the second write logic 0 at 31 ns. Its switching time is about 6.1 ns because the write current is degraded by the radiation induced current path. The radiation-induced current is about 187 μ A and the lasting time is about 4 ns. If the applied write duration time is less than 6.1 ns, a write failure will occur.

B. Read Failure

For read failure analysis, we first demonstrate the read decision failure mechanism of 1T1MTJ with particles striking and then perform evaluations on practical sense circuits.

1) Decision Failure Mechanism: The cross section of the 1T1MTJ cell and the sense current path is shown in Fig. 11. For reading one bit data stored in MTJ, a small current is applied into 1T1MTJ. The resulted voltage drop on 1T1MTJ is sensed out and then compared with a reference voltage by a well-designed sensing amplifier to determine the resistance state of MTJ. For an ideal read operation, the sensing out voltage can be obtained by

$$V_{\text{sens}} = I_{\text{read}}(R_{\text{DS}} + R_{\text{MTJ}}).$$

If radiation stroke on the access transistor when performing read operation from MTJ, a temporary channel is also generated from drain region to substrate. Since there is additional current flowing through this temporary channel, the sensed out voltage could be affected by such an unexpected change. From the equivalent schematic, the voltage to be sensed out V'_{sens} can be obtained by

$$V'_{\text{sens}} = I_{\text{read}}(R_{\text{DS}} \parallel R_{DB} + R_{\text{MTJ}}).$$

The induced temporary channel resistance R_{DB} is connected with R_{DS} in parallel, which could be viewed as a modulation effect of channel effect. This effect could eventually shift the sensed out voltage, and subsequently leads to potential read decision failures.

Assuming that the applied read current I_{read} is ideally preserved at a constant level, the high-low sensed voltage margin



Fig. 12. Circuit diagram for the implementation of 1T1MTJ read operation.

is usually defined from $I_{read}(R_{DS} + R_{AP})$ to $I_{read}(R_{DS} + R_P)$ while the reference voltage is defined as the middle of the margin. Under the channel resistance modulation effect, its voltage sensing margin is from $I_{read}(R_{DS} || R_{DB} + R_{AP})$ to $I_{read}(R_{DS} || R_{DB} + R_P)$. Hence, the original sensing margin is shifted down due to the resistance R_{DB} .

For typical implementation, MTJ resistance varies from 2 to 6 $K\Omega$ and MOS channel resistance is about 30 $K\Omega$ (saturation region when $V_{\rm DS}$ is larger than 0.5 V for nMOS in PTM LP model [22]). The radiation modulated temporal channel resistance is decided by the particles strength and varies from time to time. For typical using, we assume it is same as the MOS channel resistance 30 $K\Omega$. When reading the MTJ by applied 30 μ A with no radiation strike, its sense margin is from 960 to 1080 mV, and reference level is set as 1020 mV. Under radiation effect, the sense margin is from 510 to 620 mV. For reading a high-resistance state, the sensed out voltage is eventually less than 620 mV while the MTJ resistance state will be decided as low and result in a read decision failure.

2) Decision Failure Evaluation: A conventional sense amplifier is adopted for 1T1MTJ read operation in this paper as shown in Fig. 12, which is composed of a two-branch sensing circuit with equalizing transistors [30], a voltage sense amplifier with dynamic latched comparator [31], and a D flip-flop for digital output. The sense circuit includes a data branch for 1T1MTJ data cell and a reference generator for 1T1MTJ reference cell. Each branch consists a load pMOS, a read enable nMOS and a clamp nMOS. The source of load pMOS is directly connected to the supply voltage. The read enable nMOS is turned on by setting read enable as high to enable the read operation. The clamped nMOS is applied by a proper voltage bias to ensure a low-current sensing in order to prevent potential read disturbance. The access transistors of the paired cells share the same WL. The MTJ resistance state of reference cell is usually set as between R_P and R_{AP} so that both AP state and P state of data cell could be identified correctly. Due to the existing difference between data path resistance



Fig. 13. Waveform of read decision operation with a particle strike (MTJ with AP state for high resistance).

and reference path resistance, there exists a current difference between the data current I_{data} and reference current I_{ref} . Since the load pMOS is connected to *Vdd*, the current difference is converted into a voltage difference between V_{data} and V_{ref} . The sense amplifier (SA) is implemented by a dynamic latched voltage comparator with clock enabled [31]. At each rising edge of input clock signal V_{clk} , the SA compares the voltage difference and latches the complementary results as Out*P* and Out*N*. Finally, the compared result Out*P* is latched by D-Flip-Flop (DFF) for output for each rising edge of D_{clk} if necessary.

If a particle strike on the access transistor, the induced current is still modeled as a temporal transistor connected into ground in parallel with the access transistor and controlled by an eventually applied voltage Rad as shown in Fig. 12. The temporal nMOS is turned on by setting the input voltage Rad as high when the radiation occurs on the sensitive region of access transistor. Then the path resistance across the data cell is decreased by the introduced temporal nMOS path and additionally a transient current I_{rad} is generated through it. Under such effect of channel resistance modulation, the sense current of data cell I_{data} is the sum of current through the access transistor and leakage current through temporal nMOS. For reading a data cell 0 with P state of MTJ, V_{data} should be smaller than V_{ref} due to its low-resistance value. The radiation-induced current could enhance the current difference between the two branches. And subsequently the resulted voltage difference is enlarged so that the operation could be finished correctly. But for reading a date cell 1 with AP state, V_{data} should be larger than V_{ref} due to its high-resistance value. Under the radiation effect, Idata will be enlarged due to the temporally degraded path resistance of data cell. Hence, the voltage drop on load pMOS will be enlarged and V_{data} becomes smaller. Especially, when the degraded V_{data} is no longer larger than V_{ref} , the sensed out voltages will lead to a wrong compared result.

The comprehensive simulation results are shown in Fig. 13 for reading one bit 1 with MTJ of *AP* state. V_{clk} and D_{clk} are the input clock for voltage comparator and output DFF.

The bias voltage of load pMOS is set as $V_{\text{load}} = 500 \text{ mV}$ and clamp nMOS is set as $V_{\text{clamp}} = 900 \text{ mV}$. The data cell is read for twice starting from 5 and 25 ns, respectively. For the first read, V_{data} is about 1055 mV and V_{ref} is about 1024 mV. The compared results OutP and OutN are shown to be high and low, respectively. After the rising edge of D_{clk} at 10 ns, the final result is shown as high correctly, which indicates that the first read is performed as expected. For the second read after 25 ns, a radiation-induced SEU occurs from 27 to 31 ns. And unfortunately, the rising edges of V_{clk} and D_{clk} start within the radiation duration period to compare and latch the voltage differences. The current flowing through the data cell path V_{data} is degraded as about 962 mV which is smaller than V_{ref} . The comparing results of OutP and OutN are shown as opposite levels, respectively. And the final result is read as 0 which indicates that a wrong value is read out and a read failure is generated.

C. Build POF of 1T1MTJ Cell

We first build the radiation-induced POF of a single 1T1MTJ cell. As mentioned above, transistors containing a reversed p-n junction are sensitive to particle strikes. The access transistor to in 1T1MTJ cell is only sensitive to radiation when it is turned on among read/write operations. If the access transistor is struck with a particle, parasitic current pulse is generated which may eventually lead to a change for the write/read operation.

The effect of transient current pulse shape on POF is also evaluated and some previous results [32] have shown that POFs have no significant sensitivity to the current pulse shape but similar charge causes the almost same POF. Hence, the variation of collected charge magnitude is also adopted as one important parameter for building POFs. The POF of a 1T1MTJ cell is a function of the radiation-induced current pulse magnitude, the strike arriving time, the write current magnitude and duration time. For each particular operation, POF is a deterministic binary value in which could lead to an operation failure or not. In fact, the strike arrival time is unknown in advance and usually generated stochastically during the period of each operation. Hence, the POF is obtained by performing MC simulations for the possible arriving time. These POFs of 1T1MTJ cell failure characteristics are built as Boolean LUTs for different strike magnitudes, write current magnitudes and duration time. For MTJ switching failure, numerous MC simulations are performed to obtain the delayed switching time. If the delayed switching time is longer than the specified duration period, a writing failure will occur.

VI. SOFT ERROR ANALYSIS OF MEMORY ARRAYS

In this section, we first demonstrate the analysis flow and FIT evaluation results using physical-based MTJ switching model. And then the practical implementations of read and sense circuits are evaluated for bit error rate (BER) analysis.

A. Failure in Time Rate Estimation

In this section, the methodology to estimate the soft error rate (SER) for the entire STT-MRAM array is explained. Since a single particle strike can hit multiple MOS transistors for different 1T1MTJ cells, we evaluate SEU rates by taking the memory array layout into consideration. In order to estimate the overall SER due to particle strike, we provide several steps to obtain the POFs of different cells for a simple memory array as follows.

- Step 1: A random particle with a random direction and position is generated, and the struck transistors can be determined according to their positions in memory layout.
- Step 2: The cell operation mode is evaluated for each struck transistor, and the struck transistor whose cell is during write operation is determined as sensitive one. The relative radiation arrival time is also figured out.
- Step 3: For each sensitive transistor, the fitting parameters of double exponential model is obtained from the built LUTs of radiation-induced current transient current profile.
- Step 4: The total POF is computed for STT-MRAM array as a function of single 1T1MTJ cell POFs as

$$POF_{tot} = 1 - \prod_{i} (1 - POF(cell_i))$$

where $POF(cell_i)$ is the POF of cell *i*, and POF_{tot} is the total failure probability of whole memory cell which indicates that at least one cell is in failure.

Step 5: The above steps are performed iteratively for particles with different directions and arrival time. The overall POFs of STT-MRAM array are obtained by the averaging over all iterations.

B. Soft Error Validation Using Physical Model

In this section, the simulation results are presented using physical-based MTJ switching model. The nMOS transistor is simulated by Silvaco TCAD Atlas [26] to capture the transient current response due to radiation strike while the corresponding LUTs are built according to different strike strength and angles. The soft error POFs of one 1T1MTJ cell are characterized by the compact MTJ switching model with different radiation arrival time (1 ps time step), write current magnitude and duration time. For this experiment, we assume that the particle definitely hits the layout of the memory array under investigation. The POF is determined by evaluating the write latency with a fixed write current and duration time, i.e., a failure will occur if the required write latency is longer than applied duration time. After obtaining the POF LUTs of 1T1MTJ cell, MC simulations with 10 Million iterations are performed to estimate SER for a sample 8×8 STT-MRAM array. It should be noted that the runtime of the entire flow is around tens of hours. Such an array size is large enough to illustrate our approach to obtain a realistic ratio for SEU and there is no need to explicitly consider larger arrays.

The resulted POFs (between 0.0 and 1.0) of the 8×8 STT-MRAM array is shown in Fig. 14 with random particles strike when the write current magnitude varies from 50 μ A to 100 μ A and duration time varies from 4 to 9 ns.



Fig. 14. FIT rate of a 8×8 STT-MRAM array with various write current magnitude and duration time (zero failure for some cases).

As shown in the figure, the overall SER increases by decreasing the write current magnitude or shorten the duration time. This phenomenon can be confirmed by MTJ dynamic switching due to the total energy from applied current. It indicates that the SER should be taken into consideration as a tradeoff factor for write circuit design of STT-MRAM.

C. Evaluation Results on Practical Implementations

For evaluating the write and sense circuits as shown in Figs. 9 and 12, Cadence General 45 nm PDK [33] is adopted for the MOS transistor implementation. The MTJ cells use PMA-MTJ compact model in SPINLIB [29]. The PMA-MTJ shape is 40 ×40 nm, TMR = 150%, $I_{C0} \approx 60 \ \mu$ A, and area product R.A = 5 $\Omega \cdot \mu m^2$. In order to evaluate the effects of the process variations on the read and sense reliability performance, both MOS transistors and MTJs are considered to perform MC simulations. We adopt 3σ worst-case parameters probability distributions for the transistors which includes V_{th} , channel length and width. And 1.0% variations are adopted for MTJs, including I_{C0} , TMR ratio and R.A.

Actually the radiation-induced SEUs are most likely occurred on the access transistors of memory array since the number of access transistor is much larger than of write driver and sense circuits. Hence, the final memory-scale FIT analysis does not include the reliability of write driver and sense circuits. For modeling the radiation-induced transient current, an nMOS transistor is connected into ground in parallel with the access transistor and controlled by applying a temporal voltage bias. For MC simulations, the Rad voltage source is implemented as a VerilogA model for random radiation arrival time and random radiation duration time. The radiation strength is randomly generated according to the variation of channel width of the temporal nMOS. Since the arrival events are usually described as Poisson processes in stochastic theory, the events arrival intervals satisfy exponential distribution. In our simulations, we adopt the exponential distribution for radiation arrival time and normal distributions for other stochastic variables. All simulations are conducted using Cadence Spectre and MC simulations under Virtuoso ADE XL platform with 1000 samples.



Fig. 15. 1T1MTJ cell write time evaluation for different MOS size configurations with the considerations of radiation effect and process variation.

Since the radiation-induced write failures are calculated by a specified duration period, we demonstrate the required switching time for writing 1T1MTJ cells in Fig. 9. The simulation results are shown in Fig. 15 for different MOS size configurations with the considerations of random radiation effect and process variations. The MOS channel length is fixed as 45 nm while the width varies for different configurations. The MOS channel width for the last stage inverter and access transistor is denoted as F_{inv} and F_{acc} , respectively, which represents the specified number of fingers (120 nm for each finger). There are five MOS size configurations listed below.

A:	$F_{\rm inv} = 2, F_{\rm acc} = 2$	B:	$F_{\rm inv} = 2, F_{\rm acc} = 4$
C:	$F_{\rm inv} = 2, F_{\rm acc} = 8$	D:	$F_{\rm inv} = 4, F_{\rm acc} = 2$
E:	$F_{\rm inv} = 4, F_{\rm acc} = 4$	F:	$F_{\rm inv} = 4, F_{\rm acc} = 8$

As shown in Fig. 15, the blue dash curve Orig. represents the write performance when no variations are considered. The red dash curve demonstrates the mean value μ and standard deviation σ , and the corresponding maximum/minimum values are also plotted. Experimental results indicate that increasing the driving ability of inverters is more significant to improve the write performance when compared with enlarging the size of access transistor. Meanwhile, the variation on smaller MOS size configuration has a larger deviation for switching time. For a specified write duration time, the write failures could be obtained according to the switching time profiles. These results could be utilized to optimizing the write circuit design under different performance requirements and specified constraints.

Aiming to analyze the read decision failures of the sense circuit in Fig. 12, we evaluate the effects of the bias voltage variations while MOS transistor size is fixed using typical value. Since the sense performance are mainly determined by the bias voltage of load pMOS and clamp nMOS, we specify several pairs of bias voltages on them to evaluate the BER [34] of read decision operations. For each pair of specified bias



Fig. 16. BER of 1T1MTJ cell read decision evaluation for different bias voltages with the considerations of radiation effect and process variation.

voltages, we perform MC simulations under the process variations and random radiation strikes. Simulation results are shown in Fig. 16, in which the load bias voltage V_{load} varies from 0.4 to 0.5 mV and clamp bias voltage V_{clamp} varies from 0.7 to 1.2 mV. Noticed that for $V_{\text{load}} = 0.4$ mV, the BER increases when V_{clamp} is larger. But for $V_{\text{load}} = 0.6 \text{ mV}$, the BER decreases when V_{clamp} is larger. Additionally for $V_{\text{load}} = 0.5 \text{ mV}$, the BER is not monotonously increasing or decreasing with changing V_{clamp} . Such observations indicate that comprehensive BER profiles must be evaluated when optimizing the sense circuit to improve the read performance. In general, a larger clamp voltage V_{clamp} on BL could improve the sense margin due the enlarged sense current. However, V_{clamp} cannot be designed too large due to the potential read disturbance. Simulation results indicate that the radiation-induced random current could further introduce a more complicated effect on relationship between bias voltages and sense performance. Hence, we could integrate the radiation-induced soft error analysis to the circuit design optimization flow.

VII. CONCLUSION

In this paper, we propose a comprehensive framework for radiation-induced soft error analysis of STT-MRAM. The particle struck devices are simulated using 3-D TCAD simulator to model the resulted current pulse. The statistical electrical and magnetic properties of the MTJ, i.e., the resistance switching transience and switching time is obtained by our developed compact MTJ switching model. By leveraging the 1T1MTJ cell soft error characterization, a cross layer modeling and simulation is applicable for the designers to capture the accurate radiation effects on MTJ switching and estimate the potential POFs of memory arrays. Meanwhile, the comprehensive evaluation results on practical write and sense circuits of STT-MRAM have indicated that the radiation-induced soft error is expected to play an important role in variation-tolerant and disturbance-free STT-MRAM designs.

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