Magnetic tunnel junction design margin exploration for self-reference sensing scheme

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This work investigates the magnetic tunnel junction (MTJ) design requirements for the application of nondestructive self-reference sensing scheme, a novel sensing scheme featuring high tolerance of process variations, fast sensing speed, and no impact on device reliability. Unlike the conventional sensing scheme that requires a large TMR ratio and the uniform antiparallel and parallel resistances for MTJs, the nondestructive self-reference sensing scheme is more sensitive to the roll-off slope of MTJ's R-I or R-V curve. Our purpose is to provide a guidance to facilitate MTJ design used in the nondestructive self-reference scheme. In this work, we comprehensively investigate and analyze the design matrix by considering MTJ device physical properties, such as bias voltage dependent conductance, spin torque, etc. The manuscript suggests the approaches to optimize MTJ design for better trade-off between device properties and circuit design. © 2012 American Institute of Physics. [doi:10.1063/1.3679647]

I. INTRODUCTION

Spin-transfer torque random access memory (STT-RAM) becomes a promising memory candidate for the future computing systems because of its fast access time, high density, nonvolatility, small write current, and good scalability. However, similar to all the other nano-scale technologies, STT-RAM suffers from significant process variations, which causes large distributions of the antiparallel and parallel resistances of memory cells. As the fabrication technology keeps scaling down, the process variations demonstrate more and more severe impacts. Consequently, the read failures of the conventional sense scheme using dummy cells as references increase dramatically and hence result in intolerable low yield.

Some self-reference sensing schemes were proposed to overcome bit-to-bit process variations in magnetic tunnel junction (MTJ) resistance. The conventional self-reference sensing scheme¹ compares the original value to a reference value written into the same MTJ. The two write steps incur high power consumption and long access latency, as well as raise the concern about the device reliability.

Recently, a nondestructive self reference sensing scheme (NSRS)²⁻⁴ have been proposed by leveraging the different current/voltage dependence of the antiparallel and the parallel resistance states of an MTJ. Compared to the conventional self reference scheme, NSRS significantly reduces read latency and power consumption by eliminating write steps. However, it requires a larger read current or voltage which could induce unwanted MTJ flips during read. In this work, we investigate and analyze MTJ design matrix by comprehensively considering device physical properties (such as bias

voltage dependent conductance, spin torque, etc.) and circuit considerations in NSRS. The purpose of the work is to provide a guidance to facilitate MTJ optimization with a better trade-off between device properties and circuit design.

II. NONDESTRUCTIVE SELF-REFERENCE SENSING SCHEME

The nondestructive self reference scheme (NSRS)² is based on the unique feature of MgO-based MTJ: the current dependence of the antiparallel and the parallel resistance states of an MTJ are quite different. Figure 1 shows the measured R-I sweep curve of an MgO-based MTJ with 90 nm × 180 nm cell size, under a 40 ns voltage pulse. Some points missing from the 40 ns pulse measurement are extrapolated based on DC (static) measurement. When the applied current or voltage increases, the antiparallel-state resistance of MTJ decreases rapidly. On the contrary, the parallel-state resistance merely changes as the current or voltage varies.

FIG. 1. (Color online) The measured R-I sweep curve of a typical MgO-based MTJ (Ref. 3).

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NSRS can be classified as current- or voltage-driven designs, which is determined by applying given read currents or voltages, respectively. The read operation of NSRS includes three steps. For example, in a current-driven design, first we apply a small read current I_{R1} to generate a sensing voltage $V_{O1} = I_{R1}R_{AP1}$ or $I_{R1}R_{P1}$. Here, R_{AP1} and R_{P1} represent the MTJ resistance under current I_{R1} at antiparallel (AP) or parallel (P) states, respectively. V_{O1} is stored in a capacitor. Next, a larger current $I_{R2} = 2I_{R1}$ is applied. The corresponding sensing voltage $V_{O2} = 2I_{R1}R_{AP2}$ or $2I_{R1}R_{P2}$, depending on the MTJ resistance state. To cancel out the impact of the increased read current amplitude, we use a voltage divider to produce $V'_{O2} = 0.5 V_{O2}$. Finally, the MTJ state can be detected by checking $\Delta V_O = V_{O1} - V'_{O2}$. As shown in Fig. 1, $\Delta V_{O,AP} = I_{R1}(R_{AP1} - R_{AP2}) \gg 0$ if the MTJ is at antiparallel state. On the contrary, when the MTJ is at parallel state, $\Delta V_{O,P} = I_{R1}(R_{P1} - R_{P2}) \sim 0$. In NSRS design, $\Delta V_{O,AP}$ is defined as the sense margin, which must be large enough to be detected by the sense amplifier.

Since the current or voltage in read operations are injected from the free layer to the reference layer of MTJ, the MTJ state could be flipped from AP to P, which is called as *read disturbance*. Note that the MTJ read disturbance from P to AP never happens.

III. MTJ DEVICE PHYSICS FOR SELF REFERENCE SCHEME

MTJ resistance and spin torque dependence upon biasing voltage recently have been extensively investigated through experimental and theoretical approaches.⁵⁻¹⁷ This dependence in general can be written as:

$$G_{P,AP} = G_{P,AP,0}(1 + b_{P,AP}V + c_{P,AP}|V|^{\gamma} + d_{P,AP}V^2), \quad (1)$$

$$T_{//} = T_{//,0}(b_{//}V + c_{//}|V|^{\gamma} + d_{//}V^2), \quad (2)$$

$$T_{\perp} = T_{\perp,0}(1 + b_{\perp}V + c_{\perp}|V|^{\gamma} + d_{\perp}V^2). \quad (3)$$

Where G is conductance, T is spin torque with $//$ denoting longitudinal component and $\perp$ denoting perpendicular component. The coefficients (a, b, c, d, γ, μ) are determined by electronic and spin tunneling process across the barrier.

For elastic tunneling, the terms depending upon absolute value of voltage can be dropped: $C_{P,AP} = 0$, $C_{//,\perp} = 0$. For elastic tunneling through a symmetric ferromagnetic-insulator-ferromagnetic FM/I/FM junction structure, above equation can be simplified as

$$G_{P,AP} = G_{P,AP,0}(1 + d_{P,AP}V^2), \quad (4)$$

$$T_{//} = T_{//,0}(b_{//}V + d_{//}V^2), \quad (5)$$

$$T_{\perp} = T_{\perp,0}(1 + d_{\perp}V^2). \quad (6)$$

Notice only quadratic voltage dependence terms appear in conductance and perpendicular spin torque.

For elastic tunneling through symmetric FM/I/FM structure, in the case of high tunneling barrier, coefficient $d_{P,AP}$ dependence upon barrier height and thickness can be analyti-

cally obtained through WKB approximation. According to Brinkman model:

$$d_{P,AP} = \frac{me^2 d^2}{4\hbar \phi}, \quad (7)$$

where d is barrier thickness and ϕ is barrier height, reducing tunneling barrier height for fixed barrier thickness could increase slope of resistance dependence upon voltage. However this will decrease tunneling resistance and increase spin torque magnitude. For high barrier case, MTJ resistance and spin torque is inversely proportional to exponential of energy barrier, decreasing tunneling barrier height alone could significantly decrease resistance and increase spin torque. This will cause more disturbance and error in self-reference sensing scheme. However, if barrier thickness and barrier height could be tuned in a way such that $\frac{d}{\sqrt{\phi}}$ increases and $\sqrt{\phi}d$ remains the same, there is a chance to increase resistance roll-off sensitivity and remain the same or even reduce the resistance and spin torque magnitude for less read disturbance.

Another way to manipulate resistance roll-off curve and spin torque roll-off is through asymmetric structure and/or inelastic scattering. For example, in inelastic scattering, different physics mechanism will generate different resistance roll-off and spin torque roll-off. This is reflected as different exponential of absolute value of voltage as in above formula. We will explore more general case in future publications.

IV. SELF REFERENCE DESIGN SPACE EXPLORATION

To reflect the latest research status, we selected the MTJ device demonstrated by Zhao *et al.*¹⁸ as the baseline design, and then explore the MTJ design space in NSRS by varying the key parameters. The baseline MTJ design has a dimension of $130\text{ nm} \times 50\text{ nm}$. Its tunneling magnetoresistance (TMR) ratio is 135%. The resistance area (RA) product at parallel state is $4.3\ \Omega\mu\text{m}^2$. Accordingly, R_{AP} and R_P at a close to zero current are $1567\ \Omega$ and $667\ \Omega$, respectively. The thermal stability Δ is an important parameter affecting MTJ critical switching current I_{C0} . Zhao *et al.*¹⁸ tested it in two different ways and obtained 50 and 68, respectively. Previous research works¹⁹⁻²¹ show that the roll-off slope could range from $1\text{ K}\Omega/\text{mA}$ to $8\text{ K}\Omega/\text{mA}$. To be consistent with Ref. 18, we selected a moderate value $2\text{ K}\Omega/\text{mA}$ as the baseline. I_{R1} is fixed at 0.025 mA and the read current pulse duration² is 7 ns . I_{C0} is about 0.152 mA .

Figure 2(a) shows the sense margin of the current-driven NSRS under three roll-off slopes when fixing I_{C0} at 0.152 mA . The sense margin increases as I_{R2} increases. The relationship between sense margin and roll-off slope as well as I_{R2} are both in linear manner. When changing I_{R2} from 0.1 mA to 0.15 mA without considering read disturbance, the corresponding sense margin sweeps from 25 mV to 190.5 mV .

In reality, I_{R2} is constrained by the read disturbance probability (Pr_{sw}). Theoretically, Pr_{sw} of an MTJ at a read current I_R can be expressed as²

$$Pr_{sw} = 1 - \exp\left\{-\frac{t}{\tau} \cdot \exp\left[-\Delta\left(1 - \frac{I_R}{I_{C0}}\right)\right]\right\}. \quad (8)$$

FIG. 2. (Color online) (a) Sense margin and (b) read disturbance probability vs I_{R2} under different design parameters.

Here, t is the sensing current pulse width. Δ is the thermal stability. τ is write pulse width; I_{C0} is critical switching current, which is the minimum current to switch the MTJ resistance for τ .

If the minimum requirement of the raw bit yield is set to be 99.999%, the read disturbance probability then cannot exceed 0.0001%. Figure 2(b) shows the read disturbance probability versus I_{R2} by varying I_{C0} . Constrained by the yield, the sense margin of design with 2K Ω /mA roll-off slope and 0.102 mA critical switching current turns out to be 50 mV. According to the simulation results, the applied I_{R2} must below 0.07 mA if $I_{C0} = 0.102$ mA. If we relax the requirement of raw bit yield to be 99.99%, the applied I_{R2} must below 0.078 mA.

In summary, once the roll-off slope and spin torque (i.e. I_{C0}) are determined, the applied read current decides both the sense margin and read disturbance probability. The absolute value of MTJ resistance does not affect the effectiveness of the current-driven NSRS.

NSRS can also be implemented by applying read voltage, called as voltage-driven NSRS. Two read voltages V_{R1} and V_{R2} are added on the memory cell successively to generate sensing currents $I_{O1} = V_{R1}/R_{AP1}$ and $I_{O2} = V_{R2}/R_{AP2}$ when MTJ is at antiparallel state, or $I_{O1} = V_{R1}/R_{P1}$ and $I_{O2} = V_{R2}/R_{P2}$ when MTJ is at parallel state. The data stored in MTJ can be detected by comparing I_{O1} and I_{O2} . Unlike current-driven NSRS, the absolute values of MTJ resistances have a large impact on voltage-driven NSRS. Explicitly, R_{AP} and R_P determine not only the sense margin but also the generated sensing current and hence the read disturbance probability.

Figure 3(a) shows seven MTJ designs with different parameters including roll-off slope, critical switching current (I_{C0}) and resistance at antiparallel state (R_{AP}). I_{C0} is determined by spin torque. And both I_{C0} and R_{AP} are inversely proportional to the exponential of energy barrier. Therefore, as the roll-off slope increases from 2K Ω /mA to 3K Ω /mA by reducing the tunneling barrier. Both I_{C0} and R_{AP} reduce as shown in Fig. 3(a). Here, Design 1 is the baseline as we presented in section III. The we change the roll-off slope from 2K Ω /mA to 3.2K Ω /mA. Accordingly, I_{C0} varies from 0.152 mA to 0.08 mA and R_{AP} varies from 1567 Ω to 859 Ω .

With different design parameters, Fig. 3(b) shows the corresponding sense margin and read disturbance probability of voltage-driven NSRS. The sense margin is proportional to

FIG. 3. (Color online) Sense margin and read disturbance probability comparison of different MTJ designs.

roll-off slope similar to that of current-driven NSRS. when the second read voltage is applied, the decreasing of resistance can result in increasing of current flow through MTJ. So the read switching probability is more sensitive than that of current-driven NSRS. If the requirement of yield is constrained at 99.99%, only Design 1 and Design 2 can meet the requirement. Their sense margin are 0.08 mA and 0.09 mA, respectively. If we tight the constraint of the yield requirement to be 99.999%, only Design 1 is legal.

V. DISCUSSIONS

We comprehensively study the MTJ device physics to provide guidance to facilitate nondestructive self-reference scheme. Both current- and voltage-driven non-destructive self-reference schemes have been studied analytically and quantitatively based on various MTJ device parameters with the tuning of the MTJ tunneling barrier, which manipulates antiparallel-state roll-off slope and spin torque. The simulation results demonstrate that antiparallel-state roll-off slope and spin torque of MTJ determine the sense margin and read disturbance probability, respectively for both current- and voltage-driven schemes. Only voltage-driven scheme is sensitive to the MTJ absolute resistance in its read disturbance probability.

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