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Addressing the Thermal Issues of STT-MRAM from Compact Modeling to Design Techniques

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Abstract—STT-MRAM (Spin Transfer Torque Magnetic Random Access Memory) possesses many desirable properties such as non-volatility, fast access speed, unlimited endurance and good compatibility with CMOS fabrication process. ITRS has highlighted the potential of STT-MRAM as one of the candidates for the next-generation universal memory technology. However, both the behaviors of the MTJ (Magnetic Tunnel Junction) and the CMOS access transistor, which are two basic elements of STT-MRAM, are generally temperature dependent, threatening the reliability and performance of STT-MRAM under thermal fluctuations. To investigate the reliability and performance of STT-MRAM under the temperature variation, we developed a thermal model for the PMA (Perpendicular Magnetic Anisotropy) MTJ device. With the developed model, thermal behaviors and performance of the hybrid MTJ/CMOS circuits can be characterized and thermal optimization techniques can then be studied. Afterward, a thermal-aware sensing circuit is proposed as a case study to exploit the thermal characteristics for improving STT-MRAM read reliability under the temperature variations. Our experimental results show that the proposed sensing circuit can markedly reduce the read error rate under thermal fluctuations compared with the state-of-the-art designs.

Index Terms—Magnetic tunnel junction (MTJ), read reliability, sensing circuit, STT-MRAM, thermal fluctuations.

I. INTRODUCTION

As process technology continuously shrinks, the power wall issue has become one of the most significant bottlenecks for integrated circuits [1, 2]. Especially, the leakage power consumption occupies as much as half of the total power budget in a contemporary computing system [3]. To address this problem, spintronics emerges and its related nonvolatile memory has achieved a success in the past few years, e.g., toggle MRAM in 2006 and STT-MRAM in 2012 [4-6]. Recently, STT-MRAM has even been suggested as one of the most promising candidates for the next-generation universal memory technologies by ITRS [7].

Although promising, process, voltage and temperature (PVT) variations severely affect the reliability and performance of STT-MRAM as technology downscales [8]. Until now, lots of attempts have been done to address the process and voltage variations on STT-MRAM [9-12], the impact of the temperature variation or thermal fluctuation, however, has not yet been comprehensively studied. Based on our investigations, when the temperature varies, the switching current and the TMR (Tunnel magneto-resistance) ratio of the MTJ device as well as the driving capability of the CMOS access transistor fluctuate accordingly, resulting in performance and reliability degradations of STT-MRAM. To investigate the thermal reliability and performance of STT-MRAM under the temperature variation, this paper developed a thermal model of the MTJ device. With the proposed MTJ thermal model, the behaviors of the hybrid MTJ/CMOS circuit under the temperature variations can then be characterized and the corresponding thermal optimization techniques can be studied. Afterward, a thermal-aware sensing circuit is proposed as a case study to exploit the thermal characteristics for improving STT-MRAM read reliability under the temperature variations.

The rest of this paper is organized as follows. Section II introduces the thermal issues of STT-MRAM, and Section III models the thermal behaviors of MTJ. A thermal-aware sensing circuit is proposed and discussed in Section IV. Finally, Section V concludes this paper.

II. THERMAL ISSUES OF STT-MRAM

The typical cell structure of STT-MRAM consists of one transistor and one MTJ (1T1MTJ) connected in series as
shown in Fig. 1. The MTJ in the cell is considered as the storage element, while the transistor works as a switch to control the access condition of the cell. It also provides the bidirectional driving current to write data into or read data out from the memory cell. Due to the temperature fluctuations, failures may occur in STT-MRAM. These failures can be classified into three types: writing operation error, reading operation error and retention error.

**Writing operation error.** When writing data “1” or “0” into the cell, a negative or a positive voltage is applied to the cell as shown in Fig. 1(c) and (d) respectively. Writing errors may occur if the writing current amplitude is insufficient or (and) the pulse width is not long enough [13]. Generally, the writing pulse width for a memory chip is fixed, writing errors mostly result from the declined driving ability of the transistor under the temperature fluctuations [14].

**Reading operation error.** Reading error commonly has two categories, including sensing error and read disturbance. In general, a relatively larger sensing current is preferred to improve sensing margin [15]. On the other hand, the sensing current should be much lower than the switching current of MTJ to avoid the read disturbance during the reading “1” operation. Particularly, both the sensing current and switching current of MTJ varies under the temperature fluctuations, increasing the read reliability challenges. In practice, writing operation error can be robustly tackled by providing a sufficient writing current with high amplitude or (and) long pulse width. Reading operation error, however, cannot be effectively resolved in a similar way, owing to the intrinsic trade-off between sensing error and read disturbance [16]. Therefore, this paper focuses on the read reliability under the temperature fluctuations.

**Retention error.** Retention error, which depends mainly on the thermal stability factor, refers to the accidental MTJ flipping during the idle state. Unfortunately, the thermal stability factor decreases with respect to the temperature, adding challenges on STT-MRAM reliability under the temperature fluctuations.

Both MTJ and transistor are temperature dependent devices. The writing, reading and retention conditions of STT-MRAM change due to the temperature variations. Until now, the thermal property of a transistor has been investigated thoroughly. This paper focuses on the thermal behaviors of the MTJ device. There are many works on studying the switching behaviors of MTJ device under the temperature variations, but an electrical model capturing the thermal properties of the MTJ device is still missing for circuit design and evaluation [17, 18]. In this paper, we first present a compact MTJ model that includes the thermal properties. Then, a thermal-aware sensing circuit is proposed to tackle the reading operation issues in STT-MRAM.

### III. THERMAL MODELING OF MTJ

Both the critical switching current and TMR are temperature dependent [19, 20]. A compact model that describes the thermal behaviors of the critical switching current and TMR of a PMA (Perpendicular Magnetic Anisotropy) MTJ device is developed. Physical parameters of the MTJ used in this work are shown in Table I.

#### A. TMR Temperature Dependence

The TMR, defined as $TMR = (R_H - R_L)/R_L$, indicates the resistance difference between the antiparallel and the parallel states of an MTJ. Many experimental results have shown that the high resistance $R_H$ depends on the temperature; however, the low resistance $R_L$ almost keeps constant under the temperature fluctuations [21]. According to Shang's model [21], the conductance of an MTJ is expressed as follows,

$$G(\theta) = G_s[1 + \cos \theta \cdot P_{PZ}] + G_{St}$$

The first term represents the spin dependent part, and $G_{St}$ is the spin independent part ($\sim T^{3.5\pm 0.15}$) of the conductance. $\theta$ is the angle between the magnetization directions of the free layer and that of the pinned layer ($\theta=0^\circ$ or $180^\circ$ for parallel or antiparallel state respectively). $G_s = G_0 e^{T}/\sin(e^{T})$ is the
The TMR ratio of an MTJ without biasing voltage could be described by the following equation.

\[ TMR(T) = \frac{2P_1P_2(1 - \beta T^\omega)}{1 - P_1P_2(1 - \beta T^\omega) + G_0/G_r} \]  

(3)

Then under a biasing voltage, it can be expressed by [22],

\[ TMR(V) = \frac{TMR(0)}{1 + V^2/V_b^2} = \frac{2P_1P_2(1 - P_1P_2)}{1 + V^2/V_b^2} \]  

(4)

where \( TMR(0) \) is the TMR without biasing voltage at room temperature, \( V \) is the bias voltage on MTJ, \( V_b \) equals to 0.5V. The product of \( P_1 \) and \( P_2 \) can be expressed by \( TMR(0) \) as, 

\[ P_1P_2 = \frac{TMR(0)}{[TMR(0) + 2]} \]

Therefore, combining the (3) and (4), the TMR ratio under the temperature variations and biasing voltage can be expressed by (5),

\[ TMR(T, V) = \frac{2(1 - \beta T^\omega)^2TMR(0)}{1 - (1 - \beta T^\omega)^2 + [1 + TMR(0)]G_0/G_r + 2} \]

(5)

Fig. 2 shows the temperature-dependent TMR ratio of an MTJ derived from the above equation, which is consistent with the experimental results [25].

B. Switching Current and Switching Time

According to the switching time, the magnetization dynamics of an MTJ can be classified into two regimes: precessional switching regime and thermal activated switching regime [26-28]. In the follows, we will study the switching behaviors of MTJ under the temperature variations and model them in the precessional regime.

The magnetization switching dynamics of an MTJ is dominated by the spin polarized current flowing through it, and also impacted by the temperature. The critical current \( I_c \), which is defined as the smallest current to switch the MTJ state. In the precessional switching regime, the amplitude of the required switching current is generally larger than that of the critical current, and the switching time is then less than 10 ns. Because the spin polarization efficiency factor \( g \) and TMR ratio depend on the temperature, (6) can be obtained by replacing \( g \) with \( g(T) \) in Sun model [29], which depends on the temperature and is calculated with (8). In the precessional regime, the switching current and the switching time under the temperature variations can be calculated with (6) and (7) respectively [26].

\[ I_c = \frac{\alpha e H_e V_{sl}}{\mu_0 g(T)} = \frac{\alpha e E}{\mu_0 g(T)} \]

(6)

\[ \tau^{-1} = \frac{1}{\tau_0 \ln(\pi/2\alpha)} \left( \frac{I}{I_c} \right)^{\lambda - 1} \]

(7)

\[ g(T) = \frac{\sqrt{TMR(T, V)TMR(0)V} + 1}{2[TMR(T, V) + 1]} \]

(8)

Here, \( \alpha \) is the Gilbert damping coefficient, \( \gamma \) is the gyromagnetic ratio, \( e \) is the electron charge, \( \mu_0 \) is Bohr magneton. \( \mu_0 \) is the permeability of free space, \( M_0 \) is the saturation magnetization of MTJs ferromagnetic layers, \( H_e \) is the magnetic anisotropy field, \( V_{sl} \) is the volume of free layer and \( E \) is the energy barrier. \( \theta_0 \) is the initial angle of the magnetization direction of the free layer, which is thermally distributed and can be calculated by \( \theta_0 = \frac{\sqrt{TMR(T, V)TMR(0)V} + 1}{2[TMR(T, V) + 1]} \) [30]. \( \tau_0 \sim 1.0 \text{ ns} \) is the relaxation time, and \( \lambda \) is a coefficient \( \lambda = 0.2333 \), \( I \) is the writing current. As can be seen, when the temperature elevates, \( \theta_0 \) increases, providing a larger spin torque to help MTJ...
magnetization switching [29]. In this case, MTJ switching time reduces under a high temperature, which has been experimentally verified [28, 31]. Fig. 3 shows the simulation results with the thermal model in the precessional regime.

IV. STT-MRAM SENSING CIRCUIT DESIGN UNDER THE TEMPERATURE FLUCTUATIONS

As discussed above, the read reliability is heavily affected by thermal variations. In this section, we present a thermal-aware sensing circuit to effectively tackle this problem.

A. PCSA and Its Temperature Dependences

Fig. 4 shows the schematic of a typical sensing circuit of STT-MRAM, named pre-charge-sensing amplifier (PCSA) [32], which is composed of two inverters (MP1, MN0 and MP2, MN1), two PMOS transistors (MP0, MP3) in parallel with MP1 and MP2 respectively. NC0 and NC1 work as the clamp transistors, NA0 and NA1 are the accessing transistors of the data cell and the reference cell respectively. The sensing procedure is as follows: Vpre and Ven are set to ‘0’ from ‘0’, and Vclamp is enabled, the discharge current I0 is larger than I1, QM will decline faster than QM. As QM reaches the threshold voltage of inverter, QM will discharge to ‘0’, and QM increases to ‘1’.

\begin{align*}
\text{Equation 9:} & \\
\text{Equation 10:} & \\
\text{Equation 11:} &
\end{align*}

It is found that the sensing margins are inversely proportional to the temperature by calculating them. The reading operation error rate is determined by the amplitude of the sensing margin. Larger sensing margin is preferred to obtain lower reading operation error rate. In order to increase the sensing margin when the temperature increases, one practicable way is to increase the sensing current. Increasing transistor channel width can increase sensing current, but its amplitude cannot be tuned automatically under the temperature fluctuation, and will seriously result in read disturbance if sensing current is too large. Therefore, it is critical and beneficial to compensate sensing current automatically in high temperature without aggravating read disturbance. In the follows, it provides a thermal-aware circuit to control the gate voltage of NMOS transistor, and then automatically compensate the sensing current loss.

Fig. 5. The schematic of TAC. The left part is TAC, and the right part is designed for comparative experiments. The MTJ MTJr in TAC is configured as antiparallel state in case of being switched, while the NMOS NR works in the saturation region. Thus, a thermal-aware output voltage Vout is obtained. The amplitude of Vout can be tuned by adjusting Vs and Vbias. When the temperature increases, the current of NMOS declines. However, the current of NC3 can be compensated by Vout, which increases with the temperature, while the current of NC1 reduces due to the fixed gate voltage Vg1. Experiment results are shown in Fig. 6, Fig. 7 and Fig. 8.
### TABLE II

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>MTJT</td>
<td>the MTJ used in TAC</td>
<td>Antiparallel</td>
</tr>
<tr>
<td>TMR</td>
<td>tunnel magnetoresistance ratio of MTJT</td>
<td>200%</td>
</tr>
<tr>
<td>$V_{bias}$</td>
<td>voltage bias of NT</td>
<td>1.2V</td>
</tr>
<tr>
<td>$V_{dd}$</td>
<td>drain potential of both NC0 and NC1</td>
<td>1.0V</td>
</tr>
<tr>
<td>$W_{N莫斯}$</td>
<td>the channel width of NMOS used in TAC</td>
<td>240nm</td>
</tr>
<tr>
<td>$L_{Nmos}$</td>
<td>the channel length of NMOS used in TAC</td>
<td>45nm</td>
</tr>
</tbody>
</table>

#### B. Proposed Thermal-aware Circuit (TAC)

Fig. 5 shows the schematic of the proposed thermal-aware circuit, which comprises an MTJ (MTJT) in the antiparallel state and an NMOS transistor (NT). $V_{out}$ is the output of this TAC. The circuit is configured with the parameters listed in Table II. As indicated in the last section, the resistance of MTJT in the antiparallel state reduces with the temperature, while that of NT has the contrary thermal property. Therefore, the output $V_{out}$ is thermal-aware and increases with the temperature, it can be calculated with (12). The corresponding simulation results are shown in Fig. 6.

The right part in Fig. 5 is used to carry out the comparative experiments. The simulation results are shown in Fig. 7 and Fig. 8. The gate of NC0 is controlled by $V_{out}$, while that of NC1 connects to the fixed voltage $V_{G1}$. As indicated in Fig. 8, the drain current of NC1 declines with the temperature as expected. In Fig. 7, the drain current of NC0 has few variations around $V_s=1.6V$. This region can be used to compensate for the current loss of NMOS resulted from the temperature variations, which is specified by a brown circle. Before the region, NC0 is overcompensated, its drain current increases as the temperature; while the current of NC0 is undercompensated after the region. The amplitude of the output current meets the requirement for reading the MTJ. The lower or higher drain current of NC0 can be reached by tuning $V_s$ and $V_{bias}$ in the circuit. With this knowledge, the sensing amplifier shown in subsection A will be adapted to work better under the temperature fluctuation as illustrated in the next subsection.

#### C. Proposed Thermal-aware Sensing Amplifier (TASA)

Based on the proposed TAC, the PCSA in subsection A will be adopted to enhance its reliability under the temperature variations in this subsection.

In PCSA, the reading error rate increases due to insufficient sensing current in the high temperature. The
currents cannot be however increased simply by enlarging the channel width of transistors, which may result in read disturbance when reading “1”. Note that NC0 and NC1 in Fig. 4 are transistors to clamp the voltage for reading data cell, this voltage can be changed by adjusting the gate voltage of NC0 and NC1. With this idea, PCSA is adopted with the gate voltage of NC0 and NC1, which are tuned by Vout of TAC. Thus, the TASA is proposed to harden the reading reliability.

Fig. 9. The schematic of TASA, data cell and reference cell. The upper part is TASA, which comprises TAC and the adopted PCSA; the left side is the data cell, and the reference cell is in the other side of bottom parts. While sensing, the discharge current will be compensated by the thermal-aware Vout of TAC, which helps to enhance the reading reliability.

The schematic of TASA is shown in Fig. 9, which comprises two parts. In the upside, the left part is TASA, which comprises TAC and the adopted PCSA; the left side is the data cell, and the reference cell is in the other side of bottom parts. While sensing, the discharge current will be compensated by the thermal-aware Vout of TAC, which helps to enhance the reading reliability.

With the configuration in Table III, we use Cadence environment to study reading error rate of STT-MRAM with TASA and PCSA. The Monte Carlo simulation results are shown in Fig. 10. As can be seen, the reading operation error rates with PCSA increase with the temperature varying from 300K to 500K. However, the reading operation error rates with TASA almost keep a constant under the temperature variations. The largest reduction of reading operation error rates is about 40% when the temperature rises to 500K. These results validate the thermal variation tolerance capability of the proposed TASA. Afterward, a suitable ECC (Error Correction Code) solution can be adopted to further reduce the BER (Bit Error Rate)[33].

V. CONCLUSION

In this paper, we look into the thermal behaviors of STT-MRAM and model them into a 40nm Verilog-A based PMA MTJ SPICE model. Afterward, by analyzing the reading operation failure mechanism of STT-MRAM under the temperature variations, we propose further a thermal-aware sensing amplifier (TASA) design to deal with this problem. At last, the effectiveness of TASA is evaluated by Monte-Carlo simulations in comparison with conventional sensing circuit.

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