Extended Abstracts of the 2009 International Conference on Solid State Devices and Materials, Sendai, 2009, pp703-704

Advanced Macro-Model with Pulse-Width Dependent Switching Characteristic for Spin-Transfer-Torque based Magnetic-Tunnel-Junction Elements

Sojeong Kim, Seungjun Lee and Hyungsoon Shin

Dept. of EE, Ewha W. University, Seoul 120-750, Korea
Phone: +82-2-3277-2806, e-mail: slee@ewha.ac.kr

1. Introduction

Spin transfer torque (STT) switching in magnetic tunnel junction (MTJ) is one of the most promising magnetic random access memory (MRAM) technologies because it allows for small dimension, high speed, low programming current and low power dissipation [1]. A simulation model of an STT element for a circuit simulator such as HSPICE is essential to design MRAM circuits with STT-MTJ elements. There have been several works to model basic characteristics of STT-based MTJ [2]-[3]. These models, however, do not fully represent the behavior that switching current density depends on the pulse-width of applied current. In these models an MTJ switches its magnetic polarity as soon as the write current density exceeds certain threshold regardless of the duration of the current. That may result in false self-read disturbances appearing in circuit simulations due to short noise currents. Also, the switching may occur earlier in a simulation than in a real situation, which makes timing simulation inaccurate. In this paper, we present an advanced macro model that can emulate the dependence of switching current on current pulse-width in STT-MTJ.

2. Advanced Macro-Model for STT-based MTJ

In STT-MTJ, the switching is dependent on the current pulse-width as well as the magnitude of the switching current [4]-[5]. Several papers recently revealed the relationship between the switching current and pulse-width in STT-MTJ. Thus, these results need to be integrated into the macro-model such that it can accurately emulate the switching characteristics of an STT-MTJ. In STT-MTJ, there is the bias-dependent TMR effect which is shown as an asymmetric resistance versus current characteristics(R-I loop) [6]-[7]. In our previous work, high resistance state(R_H) curves were fitted using two separate Lorentz functions to emulate the asymmetric characteristics of R_H in the R-I loop, measured by Miura's group [3],[8]. On top of that, an advanced macro-model is implemented that can emulate the dependence of switching current on current pulse-width.

First, the STT-MTJ has an experiment characteristic shown as a red line in Fig. 1 [4]. The equation for modeling the characteristic is given as

$$T_C = T_{th} \cdot \exp((E_b/kT) \cdot (1 - I_{in}/I_{th})) \cdot \quad (1)$$

In equation (1), T_c is the pulse-width for switching and T_{th} is the reference pulse-width of 1 ns [9]. E_b/kT is a constant and its value is 30.7 at 300 K [4]. I_{in} is the amount of tunneling current across the STT-MTJ, and I_{th} is the amount of current which can make the STT-MTJ switch in T_{th} period. In this model, the MTJ switches when the pulse-width of the writing current (I_{in}) is longer than T_c. It is very difficult to integrate arbitrary time-dependent functionality into a HSPICE model because HSPICE doesn't allow 'current time' to be used as a variable in a model. The duration of the writing current is detected by monitoring the charging current of the RC circuit as in the following equation,

$$I_{out} = I_{in}[1 - \exp(-t / T_0)] \cdot \quad (2)$$

In equation (2), t is the time duration of the current I_{in}, T_0 is a constant of RC delay in the RC circuit and the value is set to 1ns. I_{out} is the output current of the RC circuit. We defined $I_{critical}$ which is the output of RC circuit when t=T_c, and it is written as

$$I_{critical} = I_{in}[1 - \exp(-T_{th} \cdot \exp\{(Eb / kT) \cdot (1 - I_{in} / I_{th})\} / T_0)] \quad (3)$$

where I_{in} is the input current. We configure the model to switch if the output of the RC circuit comes to $I_{critical}$. Thus, the model doesn't switch if an input current pulse is shorter than T_c, because I_{out} cannot reach to $I_{critical}$. On the other hand, if an input current pulse is longer than T_c, the model switches when the time duration (t) becomes T_c. Thus, it is possible to detect the minimum pulse-width that is needed for switching at various writing currents.

Fig.2 is the schematic of an advanced macro model. The resistance (G_{mtj}) represents the resistance of an MTJ. It is determined by the direction, magnitude and duration of the writing current. The MTJ stays in one of three states, RL, R_{H_N}, and R_{H_P} where R_{H_N}, and R_{H_P} represent the asymmetric nature of the high resistance states. G_{mtj} gets a value among RL, function of ng1, and ng2 according to the state of the MTJ, respectively. R_{H_N} and R_{H_P} regions are emulated by GHIGH_N and GHIGH_P [3]. E_{dev} and E_{sum} realize asymmetric R_H characteristic of the R-I loop. E_{comp1} is needed for switching by using hysteresis at the switching current. E_{time} detects the required minimum pulse-width of the switching current by comparing output of the RC circuit and $I_{critical}$. E_{cri} realizes the asymmetric switching threshold of the R-I loop by setting $I_{critical\_P}$ and $I_{critical\_N}$ for positive current and negative current, respectively. E_{abs} takes the absolute value of the output of the RC circuit for easy detection of the switching time. E_{rc} realizes the RC circuit, and sets a timer by charging the input current while the current flows through the SL and BL1. I_{wr} and I_{sense} are the writing current and reading current, respectively, that are applied externally by writing (WR) or reading (RD) command signal. R_{BIT} is bit line metal resistance per cell.

3. Simulation Results

Fig. 1 show comparison of experimental data that is scaled down for a smaller junction size of 1821 nm^2 and the simulation results of the macro model. Simulation results with a pulse-width of below 10 ns are presented in the graph because the pulse-width around 10 ns is most likely to be used for writing in commercial STT-MRAM devices. Star marks in Fig. 1 show the simulation results, which are in good agreement with the value estimated by fitting the experimental data.

Fig. 3 shows the R-I loop for STT-MTJ simulated with our macro-model. Black, red and blue lines are simulation results using the writing current pulse of 1 ns, 5 ns and 10 ns, respectively. The R-I loops were obtained by increasing and decreasing the value of the writing currents gradually.

Fig. 4 shows simulated timing behaviors of an MTJ when current with various pulse-widths are applied. A~I marks reveal input current and resistance of MTJ as times goes by. As can be seen in C~D and F~G, the resistance of MTJ is switched just after 5 ns by using a writing current of 450 uA or -350 uA. On the other hand, the simulation results do not switch when the pulse-width of the current is too short, as shown in H and I. Also, there is no switching if the magnitude of the writing current is not high enough, as shown in J and K. In Fig. 4, resistance stays at R_L state when the switching conditions are not satisfied. The opposite case, which is staying at R_H state, was confirmed the same. The result is in good agreement with Miura's data and it reveals the capability of the macro model to emulate the characteristics of STT-MTJ. The model can be very helpful in circuit simulations of STT-MRAM.

4. Conclusions

In STT-MTJ, the switching current is dependent on the pulse-width of current-induced magnetization switching. Therefore, a developed macro model considering the pulse-width of the writing current is very important for circuit designs, in order to avoid read disturbance and to precisely control the amount of current. In this paper, we present an advanced macro model that can emulate the dependence of the switching current on the pulse-width in STT-MTJ. The model successfully reproduces the switching characteristics in STT-MTJ. This macro-model can be helpful for accurate simulation of STT-MRAM with CMOS peripheral circuit in HSPICE simulator.

Acknowledgement

This work was supported by the National Program for Tera-Level Nanodevices of the Ministry of Science and Technology, as a 21st century Frontier Program.

References

[1] Y. Huai et al., *Jpn. J. Appl. Phys.*, vol. 45, p. 3835, 2006.
[2] S.Lee et al., *Intermag.*, GD-11, 2008.
[3] W. Zhao et al., IEEE *Behavioral modeling and simulation workshop*, pp. 40-43, Sep. 2006.
[4] M. Morota et al., *J. Appl. Phys.*, vol. 103, 07A707, 2008.
[5] R. H. Koch et al., *Phys. Rev. Lett.*, vol. 92, 088302, 2004.
[6] S. Yuasa et al., *Nature materials*, p. 868, Oct. 2004.
[7] M. Hosomi et al., *Int. Elect. Dev. Meeting*, p.459, Dec. 2005.
[8] K. Miura et al., *Symp. on VLSI Tech.*, p. 234, June 2007.
[9] Z. Li et al., *Phys. Rev. B.*, vol. 69, 134416, 2004.

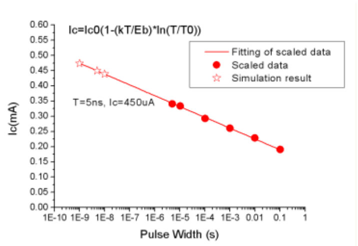

Fig. 1. Comparison of experimental data and simulation results.

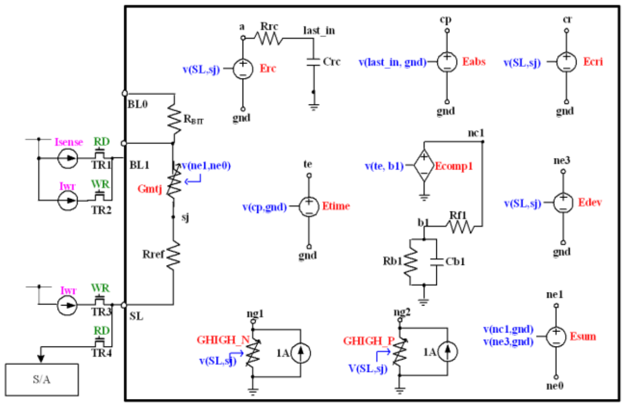

Fig. 2. Schematic of the advanced macro-model for STT-based MTJ element.

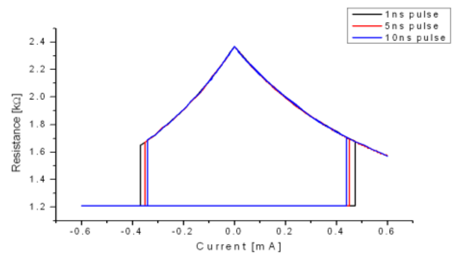

Fig. 3. HSPICE simulation results with various input pulse(R-I loop).

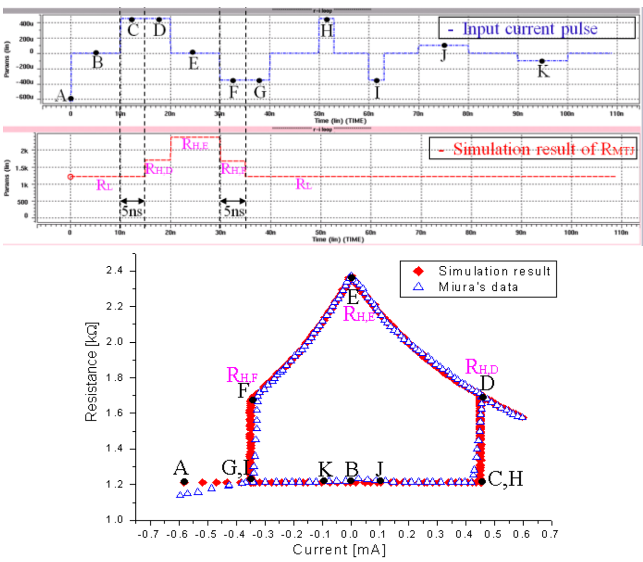

Fig. 4. HSPICE simulation results with various input pulse.