Extended Abstracts of the 2004 International Conference on Solid State Devices and Materials, Tokyo, 2004, pp. 642-643

P10-2

An Advanced HSPICE™ Macro-Model for Magnetic-Tunnel-Junction

Seungyeon Lee, Seungjun Lee, Hyungsoon Shin and Daejung Kim*

Dept. of IEE, Ewha Womans University, Seoul 120-750, Korea
Tel: +82-2-3277-2806, Fax: +82-2-3277-3494, e-mail: slee@ewha.ac.kr
*School of Electrical Engineering, Kookmin University, Seoul 861-1, Korea

Introduction

Magneto-resistive Random Access Memory (MRAM) using Magnetic Tunnel Junction (MTJ) element has a potential for revolutionizing both high-density and high-speed memory applications with devices exhibiting non-volatility and good write endurance. [1] Design of effective MRAM circuits using MTJ requires an accurate model which can exactly and effectively emulate the characteristics of an MTJ in a circuit simulator. In this work, we model various characteristics of an MTJ as a circuit macro-model that can be easily incorporated into HSPICE™ simulations [2].

The Macro-Model

The graphs in Fig.1 show the characteristics of an MTJ. Fig. 1(a) shows the hysteresis shrinking as the operating temperature of the cell increases [3]. Fig. 2(b) show asteroids where writing bit line current (Iwb) and digit line current (Idg) induce easy- and hard-axis fields, respectively [4]. These also shrink as the operating temperature of the cell increases. Fig. 1(c) shows the R-V characteristic of an MTJ [5]. As shown, the MR value varies with the voltage applied to the MTJ, and the MR ratio is reduced considerably when the bias voltage reaches a critical voltage.

As shown in Fig. 2(a), the macro-model is realized as a five terminal sub-circuit. Iwb flows through sn1~wb0 and Idg flows through dg1~dg0 for writing operation. Sense current (Isense) flows through MTJ from sn1 to sn0 for reading operation. Fig. 2(b) shows the schematics of the entire sub-circuits contained in the macro-model. The model doesn't include Idg, Iwb and Isense. Those currents are supplied externally.

Embodiments of the hysteresis and the asteroid curve dependent on the operating temperature of MTJ

In this section, we describe the hysteretic characteristics and the asteroid curves with thermal variation, which are embodied in part (i) of Fig. 2(b). A straight line approximates the measured asteroid curve in Fig. 1(b) and the macro-model uses the x- and y-intercepts as the parameterized variables. Temperature values are incorporated as parameterized variables including TL, TH, and TD, which mean the low-, high-, and desired-operating temperature of the cell, respectively.

$$\frac{X1}{Y1}\left|Idg\right| + X1 < Iwb \qquad (1)$$

$$\frac{X2}{Y2}\left|Idg\right| + X2 > Iwb \qquad (2)$$

The resistance of MTJ is R_H if (1) is satisfied, whereas, it is R_L if (2) is satisfied. Ecomp controls the thresholds values, i.e. Irefhigh and Ireflow, of hysteresis as in (3). Volow and Vohigh are the output values of node n4 in Ecomp. To model the asteroid curves having temperature dependency, the output node of Ecomp has to hold the values satisfying (4).

$$\mathrm{Ireflow} = \mathrm{Volow}\cdot\frac{\mathrm{Rb}}{(\mathrm{Rb}+\mathrm{Rf})} \qquad (3)$$
$$\mathrm{Irefhigh} = \mathrm{Vohigh}\cdot\frac{\mathrm{Rb}}{(\mathrm{Rb}+\mathrm{Rf})}$$

$$\mathrm{Volow} = \frac{(\mathrm{Rb}+\mathrm{Rf})}{\mathrm{Rb}}\cdot\left(\frac{-\mathrm{X2}}{\mathrm{Y2}}\cdot\frac{\mathrm{abs}(\mathrm{v}(\mathrm{dg1},\mathrm{dg0}))}{\mathrm{RDG}}+\mathrm{X2}\right)$$
$$\mathrm{Vohigh} = \frac{(\mathrm{Rb}+\mathrm{Rf})}{\mathrm{Rb}}\cdot\left(\frac{-\mathrm{X1}}{\mathrm{Y1}}\cdot\frac{\mathrm{abs}(\mathrm{v}(\mathrm{dg1},\mathrm{dg0}))}{\mathrm{RDG}}+\mathrm{X1}\right) \qquad (4)$$

Actual TMR values of MTJ having hysteresis, asteroid curve and R-V characteristics

Part (ii) of Fig. 2(b) is the corresponding circuit for the effective MTJ cell. The active Gmtj gets the hysteretic and the asteroid characteristic, shrinking with the increase of operating temperature, by part (i) of Fig. 2(b) during writing operation. Also Gmtj gets the R-V characteristic by part (iii) of Fig. 2(b) during reading. The method to reproduce the R-V characteristic is presented in the follow section.

Embodiments of R-V characteristics for MTJ

Now we introduce the Gaussian fitting circuit that makes the model have R-V characteristic of an actual MTJ for reading operation. The measured R-V characteristic is fitted by the Gaussian function as shown in Fig. 1(c). Eq. (5) is the Gaussian fitting form, where Ri, Ai, Vi, and Wi are incorporated as parameterized variables, and v is the bias voltage across the MTJ. As shown in part (ii) and (iii) of Fig. 2(b), if Gmtj has a value of R_H or R_L, the voltage across the MTJ is mapped by GHIGH or GLOW, respectively.

$$R_H = R0 + \frac{A0}{W0\cdot\sqrt{\pi/2}}\cdot\exp\left(-2\cdot\frac{(v-V0)^2}{W0^2}\right),$$
$$R_L = R1 + \frac{A1}{W1\cdot\sqrt{\pi/2}}\cdot\exp\left(-2\cdot\frac{(v-V1)^2}{W1^2}\right) \qquad (5)$$

$$\begin{aligned}&GHIGH\\ &= \ln(R_H - R0)\\ &= -\frac{2}{W0^2}\cdot v^2 + \frac{4\cdot V0}{W0^2}\cdot v - \frac{2\cdot V0^2}{W0^2} + \ln\left(\frac{A0}{W0\cdot\sqrt{\pi/2}}\right)\\ &GLOW\\ &= \ln(R_L - R1)\\ &= -\frac{2}{W1^2}\cdot v^2 + \frac{4\cdot V1}{W1^2}\cdot v - \frac{2\cdot V1^2}{W1^2} + \ln\left(\frac{A1}{W1\cdot\sqrt{\pi/2}}\right)\end{aligned} \qquad (6)$$

Simulation Results

A plot of the hysteresis with varying Idg, simulated with HSPICE™, is shown in Fig. 3(a). The left-hand waveform shows the results simulated while Idg flows from dg1 to dg0, and the right-hand one shows the results simulated while Idg flows from dg0 to dg1. The hysteresis shrinks as the magnitude of Idg increases. Similarly, we confirmed that the hysteresis shrinks, with a constant Idg, as the operating temperature increases. Fig. 3(b) shows the asteroids, which is simulated with various Idgs, while the operating temperature of the cell varies. It can be observed that the proposed macro-model reproduces the asteroid curve dependent on the thermal variations. As shown in Fig. 3(c), the macro-model accurately emulates the R-V characteristic of an actual MTJ. The simulation was done with varying Isense. It can be observed how closely Fig. 3(c) resembles the graphs of Fig. 1(c).

Conclusions

This paper presents an advanced HSPICE™ macro-model for an MTJ memory cell. The macro-model accurately reproduces the hysteresis, the asteroid curve dependent on the operating temperature of the cell, and the R-V characteristic of an actual MTJ. This model makes the MTJ memory cell easily integrated with the CMOS peripheral circuits in MRAM for HSPICE™ simulation.

References

[1] S. Tehrani et al., *IEEE Trans. Magnetics, Vol. 35, p. 2814,* 1999.

[2] "Star-HSPICE® Users Manual : Vol. I~ III, Version 96.1 for HSPICE Release 96.1", *META-SOFTWARE,INC.* 1996.

[3] Takeshi HONDA et al., *Symp. on VLSI Circuits*, p. 156, 2002.

[4] M. Durlam et al., *Symp. on VLSI Circuits*, p. 158, 2002.

[5] B. Das et al., *IEEE Trans. Magnetics,* Vol. 35, p. 2889, 1999.

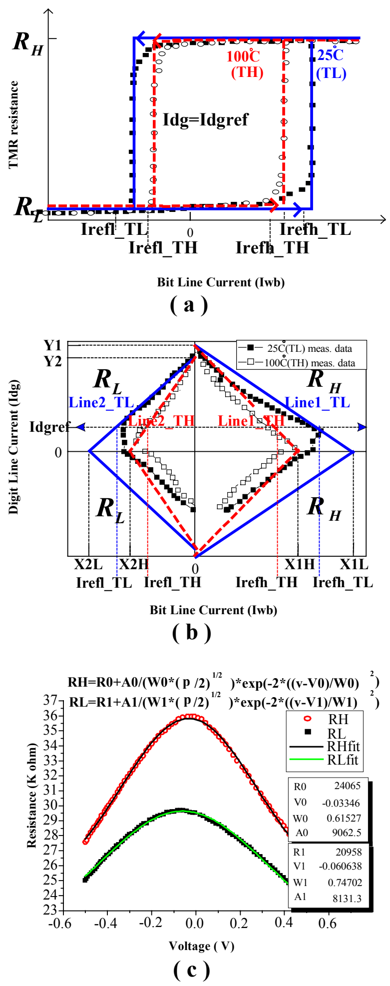

Fig. 1. (a) Hysteresis and (b) asteroid curves at 25°C and 100°C (symbols: measured data, lines: simple fitting line), (c) R-V characteristics (symbols: measured data, lines: gaussian fitting data).

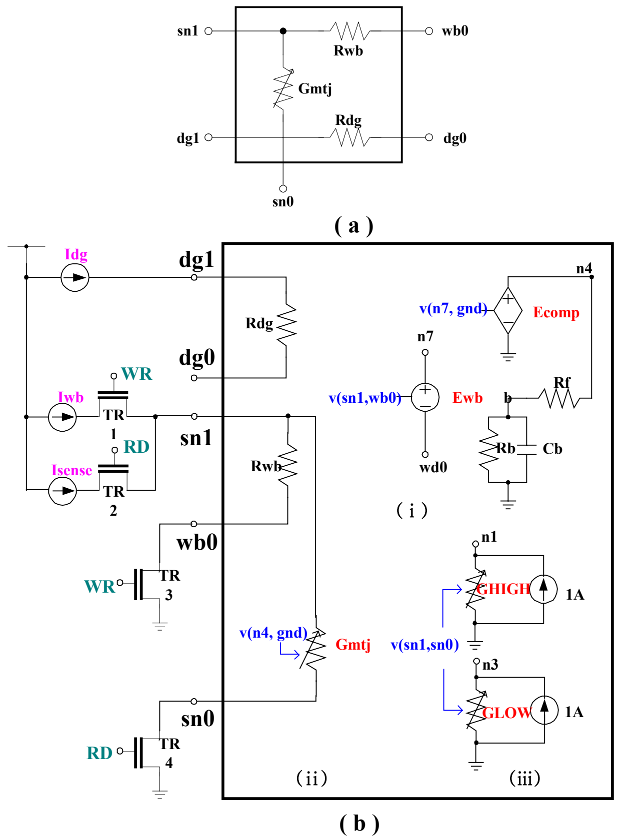

Fig. 2. (a) Block diagram and (b) schematic of macro-model for MTJ.

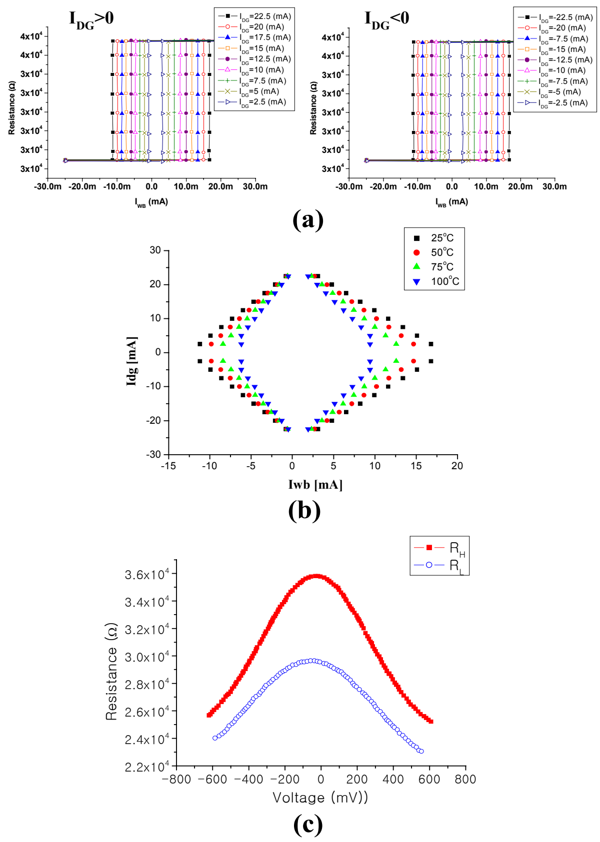

Fig. 3. HSPICE simulation results of macro-model.