Extended Abstracts of the 2016 International Conference on Solid State Devices and Materials, Tsukuba, 2016, pp939-940

PS-12-16

Stochastic Macro-model of Magnetic Tunnel Junction for Spice simulation about Writing Current Density Dependence on Resistance Variation

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Abstract

A resistance distribution of magnetic tunnel junction (MTJ) shows non-uniformity according to various MTJ parameters. This resistance variation leads to write-current density variation which causes serious problem on realizing commercial Gbit STT-MRAM. In this paper, we investigated the stochastic behavior model on write current dependence on MTJ resistance variation. The proposed model is possible to analyze the write current density according to resistance variation of MTJ with various parameter variation. It can be very helpful considering MTJ variation for designing and simulating STT-MRAM.

1. Introduction

Spin-Transfer-Torque Magneto Resistance RAM (STT-MRAM) is one of the most promising candidates for next-generation universal memory due to its non-volatility, high density, low power consumption and high operation speed. STT-MRAM is composed of Magnetic Tunnel Junction (MTJ), which is consisted of a thin tunneling oxide between pinned and free magnetization layer. The resistance of MTJ is defined to parallel state (R_P) and anti-parallel state (R_{AP}) according to magnetization angle between the two ferromagnetic layers, and the resistance difference between two states is called Tunneling Magneto-resistance Ratio (TMR) [1]. Many researches proposed macro-model based on MTJ behavior principles, but they commonly used tunnel conductance model or constant value [2-4]. In 2014, we proposed a macro-model which applied the resistance variation of MTJ according to various parameters [5]. However, the resistance variation of MTJ simultaneously affect the amount of current required for switching the state of MTJ [6], and these may cause write failure of STT-MRAM. In this paper, we investigated Macro-model of MTJ write current density (I_C) of MTJ according to resistance variation related to t_{ox}, A, T and V_b variation using Verilog-A language.

2. Stochastic Modeling of MTJ Resistance and Writing current

MTJ resistance modeling

In previous research, we fabricated a MTJ with B2-ordered Co2FeAl (CFA) full-Heusler alloy in order to observe the MTJ resistance variation tendency [5]. We proposed MTJ resistance variation model according to t_{ox}, A, T, and V_b variations [5]. Using Brinkman's tunneling conductance, resistance of MTJ at parallel state can be obtained by Eq. (1)

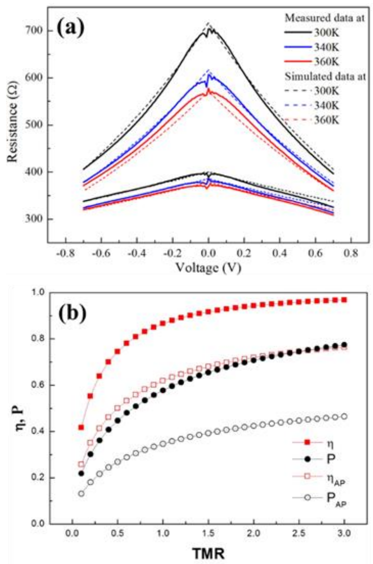

Fig. 1 (a) Comparison of MTJ resistance between simulation and measurement results and (b) the simulation results of P and η variation according to TMR variation

$$R_o = \frac{t_{ox}}{F\cdot\sqrt{\varphi_{MgO}}\cdot A}\, exp\left(1.025\cdot t_{ox}\cdot\sqrt{\varphi_{MgO}}\right) \qquad (1)$$

where t_{ox} and A is oxide thickness and surface area, and φ_{MgO} is potential barrier height for MgO which is 0.38~0.4 eV, and F is constant which is fitting parameter corresponding to t_{ox} and A [7]. Then, since the TMR is exponentially proportional to RA [8], actual TMR value according to RP variation can be obtained by Eq. (2)

$$TMR_{real} = TMR_o\cdot(1+(R_o - R_{oreal})\cdot\beta) \qquad (2)$$

where TMR_o is TMR at R_o, R_{oreal} is the resistance with t_{ox} and *A variation*, and β is constant which is variation ratio between R_P and TMR. From previous studies [9,10], we confirmed that MTJ resistance is affected by various factors below

1. Increasing T decreases the spin polarization P according to spin polarized conductance model, and leads to MTJ resistance decrement [9].
2. Since the majority spin tunneling dominates the overall conductance, R_{AP} shows much stronger dependence on temperature than R_P [10].
3. Since the bias dependence of MTJ resistance is caused by Magnon-assist tunneling, R_{AP} shows much stronger bias dependence than R_P [10].

Analyzing the effects from measured data, we realized the actual resistance modeling of R_P and R_{AP} by Eq. (3) and (4)

$$R_{Preal} = R_{oreal}\cdot exp\left(-\frac{|V_b|}{\gamma}\right)\cdot exp\left(\frac{300-T}{\eta T}\right) \quad (3)$$

$$R_{APreal} = R_{Preal}\cdot(1+TMR_{real})\cdot exp\left(-\frac{|V_b|}{\lambda\left(1+\kappa\left(\frac{T-300}{T}\right)\right)}\right)\cdot exp\left(\frac{300-T}{T}\right) \quad (4)$$

where R_{oreal} is determined from variable t_{oxreal} and A_{real}. V_b is bias voltage induced at MTJ, γ is constant related to the V_b dependence, and η is constant which related to the temperature dependence. Fig. 1 (a) shows comparison of MTJ resistance between the simulation and measured data with V_b from -0.7 to 0.7 at various temperature (300K, 340K, 360K).

Write Current modeling

As previously mentioned, the variation in resistance leads to writing current variation. With larger resistance, larger amount of current if required to change the state of MTJ. According to Z. Diao, increasing TMR contributes to reduction in Jc0 significantly [6]. This is because of Polarization factor (P) which can be calculated by Eq. (5).

$$P = \sqrt{\frac{TMR}{2+TMR}} \quad (5)$$

From the P factor, we can obtain spin transfer torque efficiency (η_{AP} and η_P). Moreover, STT efficiency shows asymmetric value according to MTJ state, and is normally lager in AP state than P state. The asymmetric characteristics has not been clearly defined by theory, and we assumed the ratio between η_{AP} and η_P by Eq. (6), where 0.6 is obtained by fitting result with P-MTJ introduces by D. Suzuki [11]..

$$\eta_{AP} = \frac{2P}{1+P^2}, \qquad \eta_P = \frac{2(0.6P)}{1+(0.6P)^2} \quad (6)$$

Fig. 1 (b) shows the simulation results of P and η variation according to TMR variation, where ideal TMR is set 1. From the STT efficiency obtained from Eq. (6), it is now able to obtain the switching current required to switch the MTJ state from AP to P and P to AP. Next, the write current density (J_C) can be obtained by Eq. (7) and (8).

$$Jco_{AP\to P} = \frac{1}{\eta_P}\frac{2\alpha e}{\hbar}(M_s t_{free})H_K = 1.5887\,MA/cm^2 \quad (7)$$

$$Jco_{P\to AP} = \frac{1}{\eta_{AP}}\frac{2\alpha e}{\hbar}(M_s t_{free})H_K = 1.5887\,MA/cm^2 \quad (8)$$

where α is Gilbert damping constant M_S is saturation magnetization, t_{free} is free layer thickness and H_K is anisotropy field.

Simulation result

P-MTJ introduced by D. Suzuki in 2014 showed 50 μA for P to AP and 70 μA for AP to P switching [11]. Based on this, we simulated by assuming that I_{CPtoAP} is 50 μA for MTJ with cell diameter of 75 nm. Fig. 2 (a) shows I_{CP} and I_{CAP} fitting results between data proposed by D. Suzuki [11] and simulation results, and Fig. 2(a) shows the simulation results of I_{CP} and I_{CAP} variation according to TMR variation with 1 % tox, 10 % TMR variation and 500 mV bias voltage. The figure indicates that this model is well fitted to previous researches, and can be well fitted for MTJ simulation.

3. Conclusions

A macro-model of MTJ resistance and switching current variation has been investigated for Hspice simulation. Our model would be helpful for the engineers to consider the resistance and switching current variation according to not only process variation but also operating conditions while performing STT-MRAM simulation.

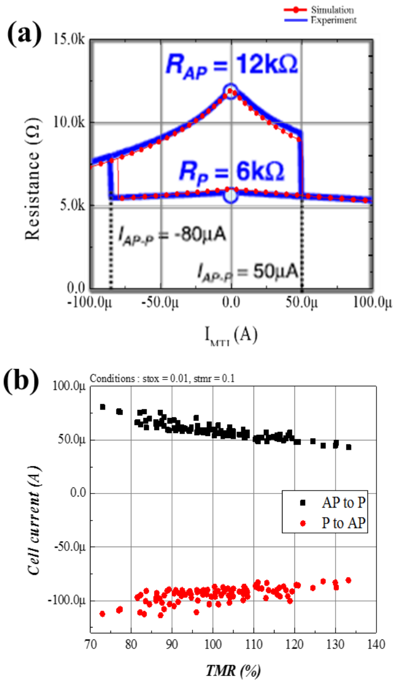

Fig. 2 (a) Comparison between measure data and simulated data and (b) the simulation results of I_{CP} and I_{CAP} according to TMR variation.

Acknowledgements

The authors would like to thank C.-K. Kim of the DRAM design team, Memory Division, Samsung Electronics Co., Ltd. for his support and helpful discussions. This research was supported by Basic Science Research Program through the National Research Foundation of Korea (NRF) funded by the Ministry of Science, ICT and Future Planning (NRF-2015R1A2A2A01007289).

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