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Stochastic Model for SPICE simulation about Resistance Distribution of Magnetic Tunnel Junction

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Abstract

A non-uniform resistance distribution for magnetic tunnel junction (MTJ) causes serious problem to realize for commercial Gbit STT-MRAM. The resistance of MTJ is varied by a combination of various causes referred to as a stochastic behavior. In this paper, we investigated a stochastic behavior model for MTJ resistance from measured real data. The proposed model can be possible to analyze an exact resistance behavior of MTJ at any parameter variation. It can be very useful for circuit design and simulation purposes.

1. Introduction

A Spin-transfer-torque magneto-resistive RAM is the best promising candidates for new generation universal memory because of its non-volatility, high density, high operation speed, and low power consumption. The storage node of STT-MRAM consists of magnetic tunnel junction (MTJ) which consists of a thin-film tunnel oxide between pinned and free ferromagnetic layers. The resistance of MTJ depends on magnetization angle between two ferromagnetic layers, which is called parallel state (R_P) and anti-parallel state resistance (R_{AP}), and the resistance difference between these states is called tunneling magneto-resistance ratio (TMR) [1]. Many researchers have proposed various macro model based on a principle of MTJ behavior [2-5]. However, the MTJ resistance model was commonly used from only tunnel conductance model or even constant value. In fact, the resistance of MTJ can be affected by not only process variations but also the operating circumstance such as oxide thickness (t_{ox}), surface (A), temperature (T), and bias voltage (V_b). For example, the varied t_{ox} and A could lead the R_P variation, affecting the variation of TMR [6]. Thus, this causes more broad variation of R_{AP}. In addition, the operating circumstance such as temperature and bias voltage significantly affects resistance variation in accordance with above case. In this paper, we investigated a stochastic model of MTJ resistance related to t_{ox}, A, T, and V_b variations, and it was confirmed in HSPICE simulation using Verilog-A language.

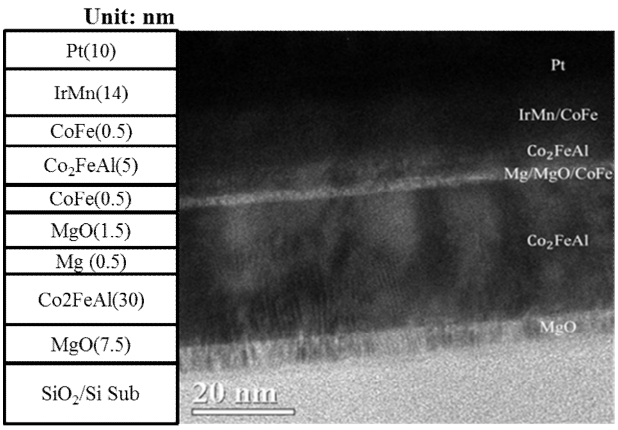

Fig. 1 Schematic of structure for fabricated $Co_2FeAl/MgO/Co_2FeAl$ full-Heusler MTJ and Cross-sectional TEM image.

2. Stochastic Modeling of MTJ Resistance

Sample preparation

In order to observe tendency for the variation of MTJ resistance, we fabricated a MTJ with a B_2-ordered Co_2FeAl (CFA) full-Heusler alloy as shown in Fig. 1. The MgO barrier thickness and size of MTJ are 1.5 nm and 10 x 5 μm^2. The R_P, TMR, and half voltage V_h (the voltage where the TMR is reduced to half of its value) are 400 Ω, 79 %, and 430mV, respectively. These high TMR and V_h indicate a good barrier quality, which also confirmed from TEM image in Fig. 1. Although fabricated MTJ sample was not the state-of-the-art, the obtained resistance characteristic is almost same with that of. Therefore, we could analyze reasonable data and investigate the model.

MTJ resistance modeling

As the MTJ current is generated by tunneling electrons through thin insulating layer, the resistance of MTJ at parallel state could be estimated by Brinkman's tunneling conductance equation as follow

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

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 α is constant which is fitting parameter corresponding to t_{ox} and A [7]. Since the R_P is varied by t_{ox} and A, and the TMR is exponentially proportional to RA value, the variation of R_P leads the TMR variation. Therefore, the real TMR can be defined as follow

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

where TMR_o is TMR at R_o, R_{oreal} is the inclusion of variation with t_{ox} and A, and β is constant which is variation ratio between R_P and TMR. Figure 2 shows the experimental

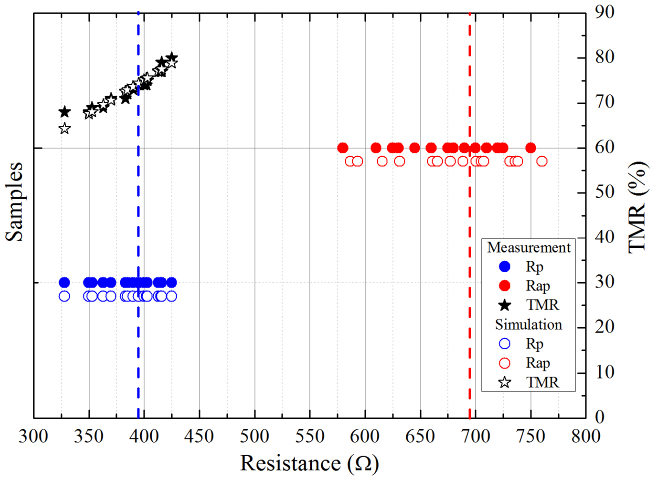

Fig. 2 Comparison between simulation and measurement results for TMR relationship with R_P distribution.

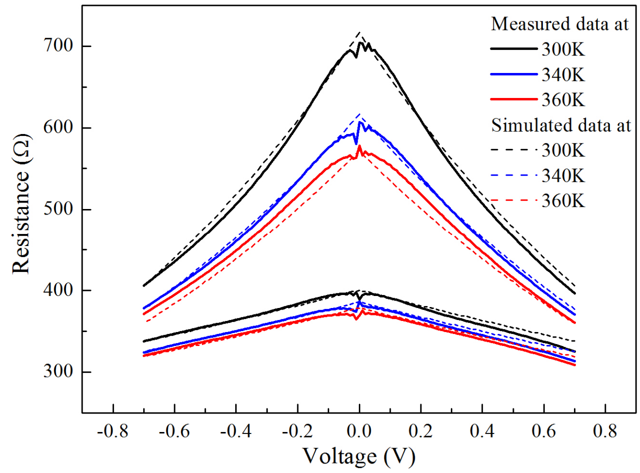

Fig. 3 Comparison between simulation and measurement results for voltage bias and temperature dependences.

results for relation between R_P, TMR, and R_{AP}. Interestingly, increasing R_P gradually increases R_{AP}, and each value of measured R_P consistently matches to each R_{AP} value. Figure 3 shows the temperature and bias voltage dependences. The MTJ resistance was measured from -0.7 V to +0.7 V at 300K, 340K, and 360K, respectively. Since the spin polarization P decreases with increasing T according to spin polarized conductance model, the temperature increment results in MTJ resistance decrement [8]. The R_{AP} has much stronger temperature dependence than R_P, because the majority spin channel tunneling dominates the overall conductance. The bias dependence is caused by magnon-assist tunneling that is spin flipping due to excitation of magnetic atoms at barrier interface [9], the R_{AP} also has much stronger bias dependence. Therefore, we estimated the real R_P with temperature and bias dependence as follow

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

where R_{oreal} is determined from variable t_{oxreal} and A_{real}. V_b is bias voltage induced at MTJ, γ is constant which related to the bias voltage dependence, and η is constant which related to the temperature dependence. All constants that are fitting parameters can be determined from measured data. Finally, we can obtain the real R_{AP} value using the equation (4), which is combined from (1) to (3) and involves new temperature and bias terms including the λ and κ parameters to complement the stronger dependences of R_{AP} as follows.

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

Simulation results

To compare with measured data, we adjusted the fitting parameters such as α, β, γ, η, λ, and κ. First, the R_O value was fitted from α, and the β was obtained from measured TMR variation ratio in Fig. 2. Then the γ and η were calculated from I-R graph in Fig. 3, and λ and κ were calculated in the same manner. The results of proposed model show in Fig. 2 and 3. The figures reveal that the stochastic resistance model matches with the measurement data well, indicating the model proposed in this paper can well fit the MTJ resistance in any parameter considered such as t_{ox}, A, temperature, and bias dependence.

3. Conclusions

We investigated the stochastic behavior model for MTJ resistance distribution to design and to evaluate the circuit such as sense amplifier for STT-MRAM because the distribution of MTJ resistance could be caused by both process variation and the operating circumstance. Our model that is not only simple but also well fitted will be very useful to estimate MTJ resistance distribution.

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