Macro-model of Spin-Transfer Torque based Magnetic Tunnel Junction device for hybrid Magnetic-CMOS design

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ABSTRACT

The development of hybrid Magnetic-CMOS circuits such as MRAM (Magnetic RAM) and Magnetic logic circuit requires efficient simulation models for the magnetic devices. A macro-model of Magnetic Tunnel Junction (MTJ) is presented in this paper. This device is the most commonly used magnetic components in CMOS circuits. This model is based on Spin-Transfer Torque (STT) writing approach. This very promising approach should constitute the second generation of MRAM switching technology; it features small switching current (~120uA) and high programming speed (<1ns). The macro-model has been developed in Verilog-A language and implemented on Cadence Virtuoso platform with Spectre 5.0.32 simulator. Many experimental parameters are integrated in this model to improve the simulation accuracy. So, the model can efficiently be used to design hybrid Magnetic CMOS circuits.

1. INTRODUCTION

Magnetic RAM (MRAM) is one of the most promising memory technologies, which features non-volatility, high reading speed, large retention time up to 10 years and it allows also more than 10^{12} re-programming cycles [1]. The elementary storage device of MRAM is the Magnetic Tunnel Junction (MTJ) [2]. By using MgO barrier in MTJs, the reading performance of MRAM has been significantly improved; however its writing performance still dominates the power consumption and the circuit surface. In the first generation of MRAM, Field Induced Magnetic Switching (FIMS) writing approach has been adopted. It uses two high currents to program the MTJ and then it leads to a high power dissipation and requires large surface transistors [1]. In the last 2 years, Spin-Transfer Torque (STT) has been introduced and rapidly developed by different companies [3-6]. Spin Transfer Torque reversing phenomena in MTJ was observed in MTJs of less than 100nm in width [7]. In addition to its small dimension (e.g. 240nm*80nm), it features high speed, low programming current and therefore low power dissipation. Simultaneously, it keeps all the good performances of the first generation of MRAM.

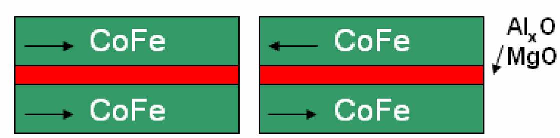
In the second section, we will introduce the STT based MgO barrier MTJ component and its physical models. The electrical macro-model and some DC/Transient simulation results will be shown in the third section. This model has been developed in Verilog-A and implemented on Cadence Virtuoso platform with Spectre 5.0.32 simulator. For the hybrid Magnetic-CMOS simulation, STmicroelectronics CMOS 90nm technology has been used.

2. STT (Spin-Transfer Torque) based MRAM

2.1 STT based MTJ introduction

STT based MTJ is mainly composed by three layers (Fig. 2.1), 2 ferromagnetic layers and one oxide barrier, here MgO. MTJ behaves as a resistor with two resistance characteristics (high and low) depending of the direction of magnetization in the two ferromagnetic layers, it presents low (respectively high) resistance when the spin transport is in the same (resp. opposite) direction in the two ferromagnetic layers. This resistance variation behavior was observed firstly by Julliere in 1975 [8]. The ratio between the two resistance values is named Tunneling Magneto resistance Ratio (TMR) and defined in Equ. (2.1). The TMR is currently up to 70% in an Al_xO barrier MTJ and 230% in an MgO barrier MTJ [2].

$$TMR = \frac{R_{AP} - R_P}{R_{Ap}} \qquad (2.1)$$



(a) (b)

Figure. 2.1 (a): Low resistance MTJ - (b) High resistance MTJ

This improvement of TMR allows a simple CMOS sensing circuit to read the information in MTJs more easily when the low and high resistance represent different bit of information.

There are currently three MTJ writing approaches, FIMS [1], TAS (Thermally assisted switching) [9] and STT. The high switching current (>mA) requirement of the first writing approach limits its applications to non volatile memories and forbids its more general use in Standard CMOS circuits. In 1996, Slonczewski showed that a threshold current density exits in MTJ and named it critical current density [10]. If the current density in the MTJ is superior to the critical current density, the MTJ resistance state changes (Fig. 2.2). The positive or negative direction of current determines the MTJ's state changing from parallel (P) to anti-parallel (AP) or AP to P. This critical current density has been found as low as

$8*10^5$ A/cm^2 [6]. As the dimension of MTJ is very small, the critical current is about 120uA and it can be easily generated by some small surface transistors on standard CMOS technologies.

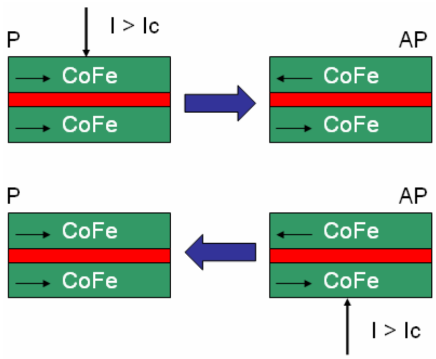


Figure. 2.2 The MTJ state changes from Parallel (P) to Anti-parallel (AP) if the positive direction current density I>Ic, on the contrast, its state will return if the negative direction current density I > Ic.

2.2 MgO barrier MTJ Resistance Model

The MTJ Conductance physical Model has been introduced by Brinkman in 1970 [11] (see Equ. 2.2 to 2.4). It features the voltage bias dependence and is deeply influenced by the height of barrier.

$$G(0) = 3.16\times10^{10}\times\bar{\varphi}^{1/2}\,\frac{\exp(-1.025\times tox\times\bar{\varphi}^{1/2})}{tox} \quad (2.2)$$

$$\frac{G(V)}{G(0)} = 1-\left(\frac{A_0\Delta\varphi}{16\bar{\varphi}^{3/2}}\right)eV+\left(\frac{9}{128}\frac{A_0^2}{\bar{\varphi}}\right)(eV)^2 \quad (2.3)$$

$$A_0 = \frac{4\times(2m)^{1/2}\times tox}{3\times\bar{h}} \quad (2.4)$$

Constants:

m: the electron mass 9.1*e-31

$\Delta\varphi$:0 (The barrier is symmetric)

$\bar{h}$: Planck's constant: 1.0545*e-34

$\bar{\varphi}$: The potential barrier height 0.4 (for MgO [2]), 2 (for AlxO)

Parameters:

tox: height of barrier in MTJ

surface: surface of the MTJ (rectangle or ellipse)

The simplified resistance equations shown in Equ. (2.5, 2.6) are used in the electrical macro-model to express the resistance performance of MTJs.

$$R(0) = \frac{tox}{223.76\times\bar{\varphi}^{1/2}\times surface}\times\exp(1.025\times tox\times\bar{\varphi}^{1/2}) \quad (2.5)$$

$$R(V) = \frac{R(0)}{1+\left(\frac{tox^2\times e^2\times m}{4\times\bar{h}^2\times\bar{\varphi}}\right)\times V^2} \quad (2.6)$$

2.3 Spin-Transfer Torque switching Model

The Spin-Transfer Torque physical model proposed by Slonczewski [10, 12] has been used in our macro-model to simulate the switching behavior of the MTJ (E.2.7-11). The most important contribution of this model is to explain how we can get the critical current.

$$J_{C0} = \alpha\times\gamma\times e\times M_s\times t\times(H_{ext}\pm H_{ani}\pm H_d/2)/u_B\times g \quad (2.7)$$

$$E = \frac{M_s\times V\times H_c}{2} \quad (2.8)$$

$$g = \left[-4+(P^{-1/2}+P^{1/2})\times(3+\cos\theta)/4\right]^{-1} \quad (2.9)$$

$$J_C = J_{C0}\left\{1-\left(\frac{k_B\times T}{E}\right)\ln(\tau_m\times f_0)\right\} \quad (2.10)$$

$$I_C = J_C\times surface \quad (2.11)$$

Constants:

Hext: the external field: -19Oe

Hani: the in-plane uniaxial magnetic anisotropy field 100 Oe

Hd: the out-of-plane magnetic anisotropy induced by the demagnetization field 13000 Oe

ζm: the measurement time 1s

f0: the attempt frequency 10^9Hz

kB: Boltzmann constant, 1.38×10-23J/K

uB: Bohr magneton constant, 9.27×10-28J/Oe

Ms: 1.3 T (CoFe) =13000 Oe

Hc: coercive field

α: Gilbert damping coefficient 0,01

γ: gyromagnetic constant =221000/2*pi

e: An elementary charge 1.60 x 10-19 C

Parameters:

t: height of the free layer(1-3nm)

Θ: parallel: 0 and anti-parallel: π

V: volume of the free layer (80×240 nm^2 ×t)

2.4 TMR effect bias-voltage dependence model

TMR effect depends on the bias-voltage between the two electrodes [2] and it is defined as a function of V and TMR (0)

$$TMR_{real} = \frac{TMR(0)}{1+\frac{V^2}{Vh^2}} \quad (2.12)$$

Parameters:

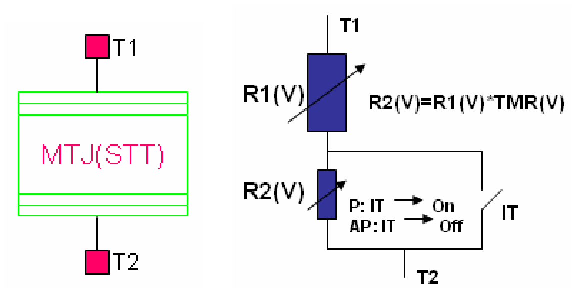
TMR (0): Resistance Ratio between low and high resistance with 0V bias-voltage.

Vh: the bias voltage where TMR_{real} =0.5*TMR (0)

3. Electrical Macro model developpent and Simulations

3.1 Macro Simulation Model

Based on the above three physical models and by using Verilog-A analog digital mixed language [13], we developed the simulation macro-model for the Spectre simulator (Fig.3.1). In order to reduce the simulation time, and as the switching speed of STT switching approach is high (less than 1ns [14]), the MTJ behavior has been considered static in the model. The dynamic model behavior which could be used for the design of RF circuits is under development.



(a) (b)

Figure. 3.1 (a) Simulation model symbol in the spectre simulator (b) Resistance equivalent circuit

3.2 DC Simulations and Transient Simulations

DC and transient simulations have been performed to verify the bias-voltage dependent resistance, TMR effect, the switching current and performance from parallel configuration (P) to anti-parallel configuration (AP) and AP to P (see Fig. 3.2 to 3.4)

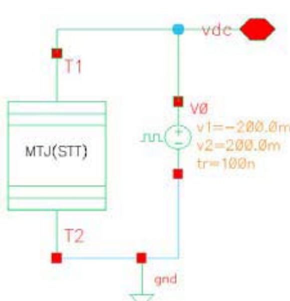


Figure. 3.2 DC and transient simulation

4. CONCLUSION

We have developed the electrical STT based MTJ macro-model, which allows us to simulate hybrid STT based MTJ and CMOS architectures, including circuits such as look up table and Flip-Flops [15]. The DC and transient simulations verify the functionality and behavior of this MTJ model. The current model is in the static mode which is suitable for the logic simulation, however the STT phenomena has many potential applications[16] such as in the field of radio frequency; therefore the dynamical switching behavior will be presented in the future.

5. ACKNOWLEDGMENT

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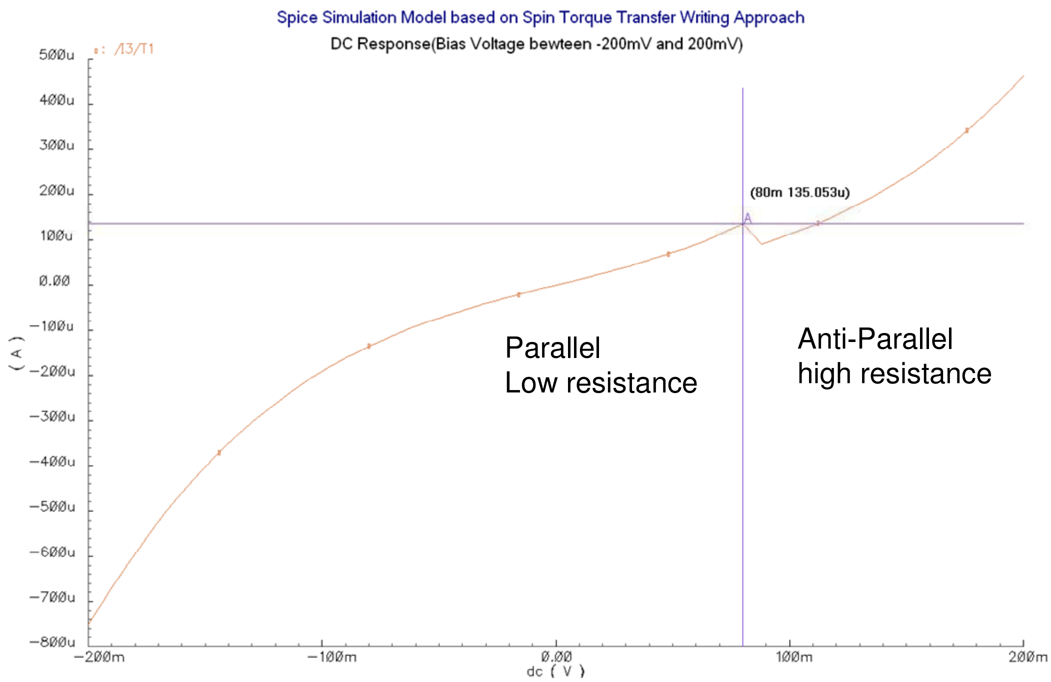

Figure. 3.3 DC simulation of MTJ (Parallel), the critical current is about 135.053uA and the potential is about 80mV

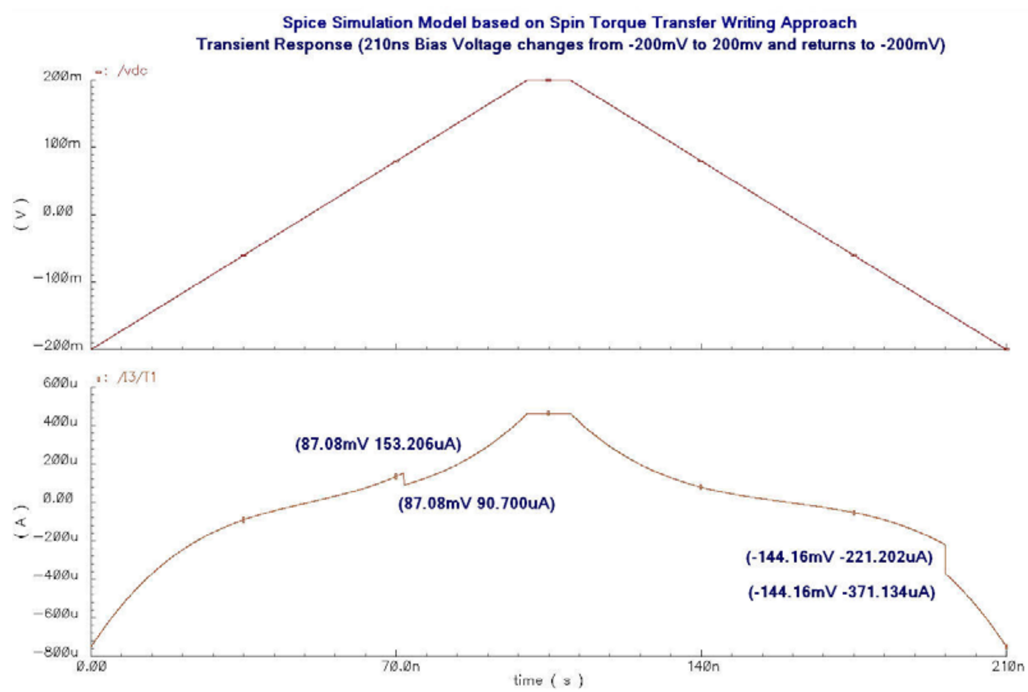

Figure. 3.4 Transient simulation of MTJ, the critical current is about 153.206uA for parallel and -221.202uA for anti-parallel