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

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Overview

- Hybrid Magnetic-CMOS design
  - MRAM (Magnetic RAM)
  - Applications: Magnetic logic, FPGAs,

- STT (Spin-Transfer Torque) based MRAM
  - STT based Magnetic Tunnel Junction (MTJ) introduction
  - Model presentation: three main equations

- Electrical Macro model development and Simulations

- Conclusion and perspective
MRAM Introduction

**Magnetic Tunnel Junction**

![Magnetic Tunnel Junction diagram]

- **Low resistance**
- **High resistance**

\[ TMR = \frac{R_{\text{high}} - R_{\text{low}}}{R_{\text{low}}} \]

**TMR (Tunnel Magnetoresistance ratio)**

- 70% with \( Al_{x}O_{y} \) barrier
- 230% with MgO barrier

*MR curves of CoFeB/MgO/CoFeB MTJs evaluated*

*Djayaprawira et al. [APL’05]*
Hybrid Magnetic-CMOS design
Writing a MTJ: 3 technologies

- **1st generation MRAM**
  - Two high currents required
  - High power dissipation
  - Large width transistors
  - \( \approx 10 \text{ à } 20 \text{ mA} \)

- **2nd generation**
  - TAS \( \approx 1 \text{ mA} \)
  - STT \( \approx 120 \mu\text{A} \)

(a) field induced writing (FIMS)
(b) thermally assisted writing (TAS)
(c) spin transfer torque (STT)
Hybrid Magnetic-CMOS design

MTJs are implemented on top of the CMOS layers
Hybrid Magnetic-CMOS design

Advantages
- Bring non-volatility property to CMOS
- High reading speed (10-20ns)
- High writing speed (<1ns)
- Large retention time more than 10 years
- High density (MTJ : 113nm*75nm)
- More than $10^{12}$ re-programming cycles

Constraints
- More fabrication masks than standard CMOS
- Power dissipation with 1st gen writing techno.
Hybrid Magnetic-CMOS design
APPLICATIONS

- MRAM memory: IBM, Freescale, ...

- Secured FPGA:

[IBM Fig.]

• 3-input LUT with non-volatile configuration (will be presented at ICSICT06, Shanghai)

• Non volatile FLIP-FLOP (presented at ICICDT06, Italy)
STT (Spin-Transfer Torque) based MTJ

The MTJ state changes:
- from Parallel (P) to Anti-parallel (AP) if current density $I > I_c^+$
- from AP to P if $I < -I_c^-$

\[ \text{CoFe} \quad \text{CoFe} \]

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The modelized MTJ is based on Co\textsubscript{40}Fe\textsubscript{40}B\textsubscript{20}/MgO/Co\textsubscript{40}Fe\textsubscript{40}B\textsubscript{20}.

3 equation sets are implemented in the behavioral model:
1. Slonczewski critical model
2. Brinkman resistance model
3. TMR effect bias-voltage dependence model
STT (Spin-Transfer Torque) based MTJ
1st eq set : Slonczewski model

\[ J_C = J_{C0} \left\{ 1 - \left( \frac{k_B \times T}{E} \right) \ln(f_m \times f_0) \right\} \]

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

\[ E = \frac{M_s \times V \times H_c}{2} \]

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

Hext: the external field: -190Oe
Hani: the in-plane uniaxial magnetic anisotropy field 100 Oe
Hd: the out-of-plane magnetic anisotropy induced by the demagnetization field 13000 Oe

\( \zeta_m \): the measurement time 1s
f0: the attempt frequency 109Hz
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

\( \alpha \): Gilbert damping coefficient 0.01
\( \gamma \): gyromagnetic constant =221000/2*pi
\( e \): An elementary charge 1.60 x 10-19 C

Parameters:
• \( t \): height of the free layer(1-3nm)
• \( \Theta \): parallel: 0 and anti-parallel: \( \pi \)
• \( V \): volume of the free layer (80×240 nm2 ×t)
STT (Spin-Transfer Torque) based MTJ
2nd eq set : Brinkman conductance model

\[
\frac{G(V)}{G(0)} = 1 - \left( \frac{A_0 \Delta \phi}{16 \varphi} \right) eV + \left( \frac{9}{128} \frac{A_0^2}{\varphi} \right) (eV)^2
\]

\[
G(0) = 3.16 \times 10^{10} \times \varphi^{-1/2} \exp\left(-1.025 \times d \times \varphi^{-1/2}\right) / d
\]

\[
A_0 = \frac{4 \times (2m)^{1/2} \times d}{3 \times \hbar}
\]

\[
R(0) = \left( \frac{\text{tox}^{-1/2}}{223.76 \times \varphi \times \text{surface}} \right) \times \exp\left(1.025 \times \text{tox} \times \varphi^{-1/2}\right)
\]

\[
R(V) = \frac{R(0)}{1 + \left( \frac{\text{tox}^2 \times e^2 \times m}{4 \times \hbar \times \varphi} \right) \times V^2}
\]

**Constants:**
- \( m \): the electron mass 9.1*e-31
- \( \Delta \phi \): 0 (The barrier is symmetric)
- \( \hbar \): Planck’s constant: 1.0545*e-34
- \( \varphi \): The potential barrier height 0.4 (for MgO [2]), 2 (for AlxO)

**Parameters:**
- \( \text{tox} \): height of barrier in MTJ
- \( \text{surface} \): surface of the MTJ (rectangle or ellipse)
STT (Spin-Transfer Torque) based MTJ
3rd eq set : TMR bias-voltage dependence model

\[ TMR_{\text{real}} = \frac{TMR(0)}{1 + \frac{V^2}{Vh^2}} \]

TMR (0): Resistance Ratio between low and high resistance with 0V bias-voltage.
Vh: the bias voltage where TMRreal = 0.5 * TMR (0)

Relation between bias voltage V and the normalized MR ratio at room temperature

Yuasa et al, Nature Materials
Electrical Macro model developed and Simulations

Simulation Environment:
1. STmicroelectronics 90nm design kit
2. Cadence spectre simulator
3. Verilog-A language

Simulation model symbol

Resistance equivalent circuit
Electrical Macro model developed and Simulations

Spice Simulation Model based on Spin Torque Transfer Writing Approach

DC Response (Bias Voltage between -200mV and 200mV)

MTJ DC simulation:
the threshold current is about 135 uA and the threshold voltage is about 80mV
Electrical Macro model developed and Simulations

MTJ DC simulation:
the threshold current is about -221uA
and the threshold voltage is about -156mV
Electrical Macro model developed and Simulations

Spice Simulation Model based on Spin Torque Transfer Writing Approach
Transient Response (210ns Bias Voltage changes from -200mV to 200mv and returns to -200mV)

MTJ transient simulation:
the threshold current is about
153μA for parallel and -221μA for anti-parallel
Conclusions and perspectives

- The model has been developed to simulate hybrid MTJ/CMOS architectures.
- The model is based on next generation Spin-Transfer Torque (STT) writing technique.
- The current model is in the static writing mode and is sufficient for the magnetic FPGA simulation.
- The dynamical switching behavior will be presented in the future.
- The main applications are the design of MRAM and Magnetic FPGA.