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

Weisheng Zhao, Eric Belhaire, Quentin Mistral, Claude Chappert
Institut d' Electronique Fondamentale
CNRS / University of Paris South, France

Virgile Javerliac, Bernard Dieny
SPINTEC, CEA, France

Elsa Nicolle
STMicroelectronics Grenoble, France

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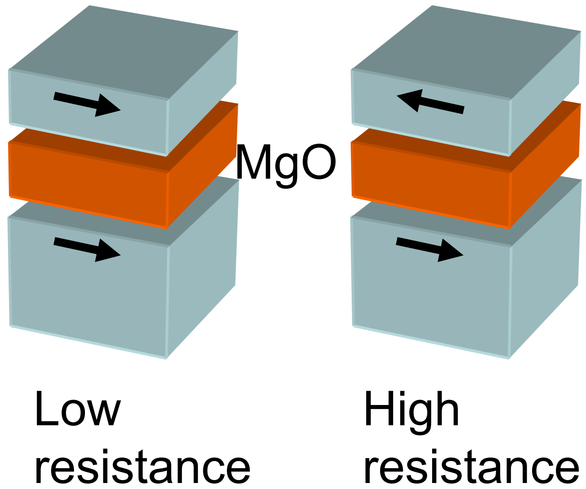
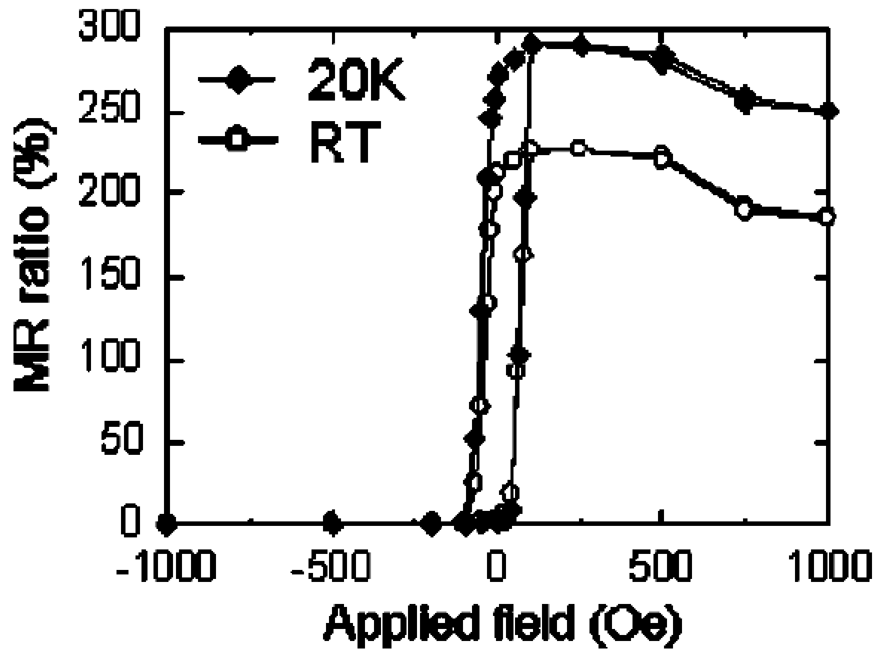
Overview

- **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





$$TMR = \frac{R_{high} - R_{low}}{R_{low}}$$

MR curves of CoFeB/MgO/CoFeB MTJs evaluated

Djayaprawira et al. [APL'05]

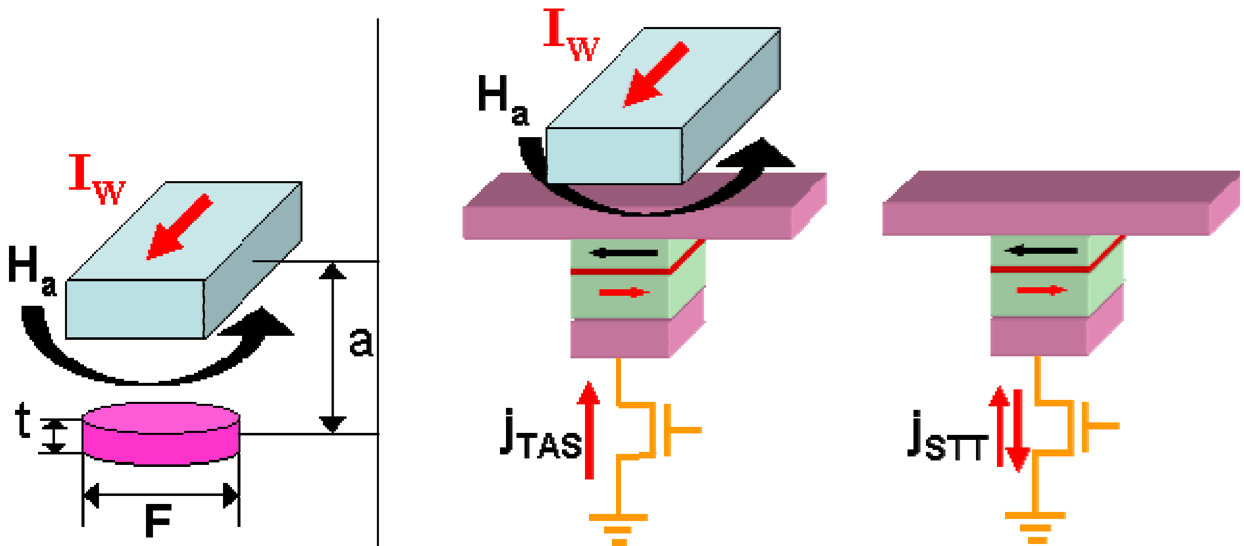
TMR (Tunnel Magnetoresistance ratio)

→ 70% with Al_xO_y barrier

→ 230% with MgO barrier

Hybrid Magnetic-CMOS design

Writing a MTJ : 3 technologies



(a) field induced writing (FIMS)

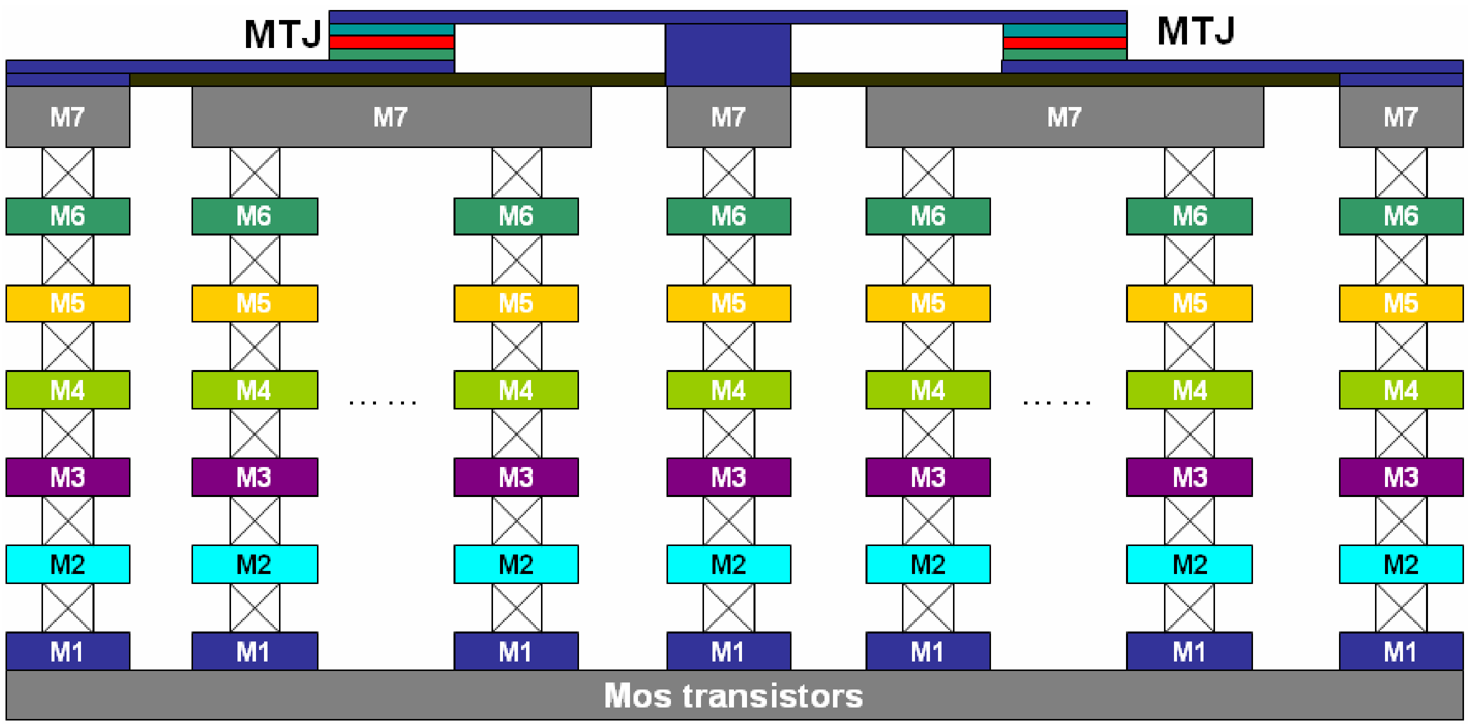
(b) thermally assisted writing (TAS)

(c) spin transfer torque (STT)

- 1st generation MRAM
- Two High currents required
  - High power dissipation
  - large width transistors
  - **≈ 10 à 20 mA**

- 2nd generation
- TAS **≈ 1 mA**
- STT **≈ 120 µA**

Hybrid Magnetic-CMOS design



MTJs are implemented on top of the CMOS layers

Hybrid Magnetic-CMOS design

Advantages

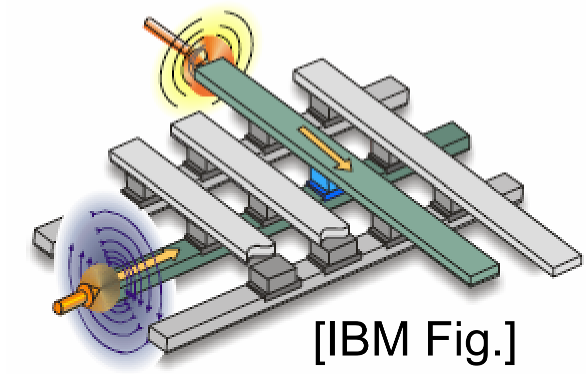
- Bring non-volatility property to CMOS
- High reading speed (10-20ns)
- High writing speed (<1ns)
- Large retention time more than 10 years
- **High density** (MTJ : 113nm*75nm)
- More than 10^{12} re-programming cycles

Constraints

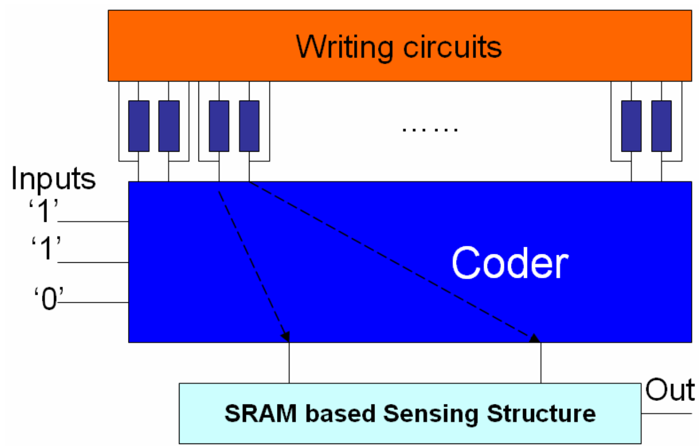
- More fabrication masks than standard CMOS
- Power dissipation with 1st gen writing techno.

Hybrid Magnetic-CMOS design APPLICATIONS

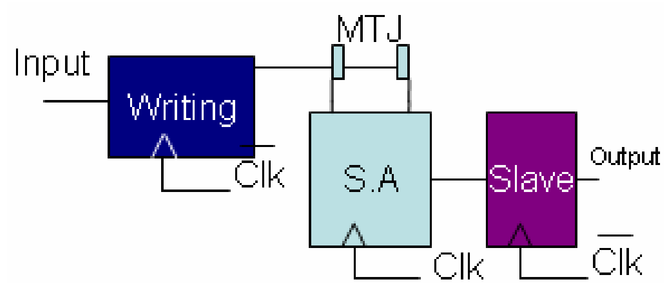
- MRAM memory: IBM, Freescale, …



- Secured FPGA:

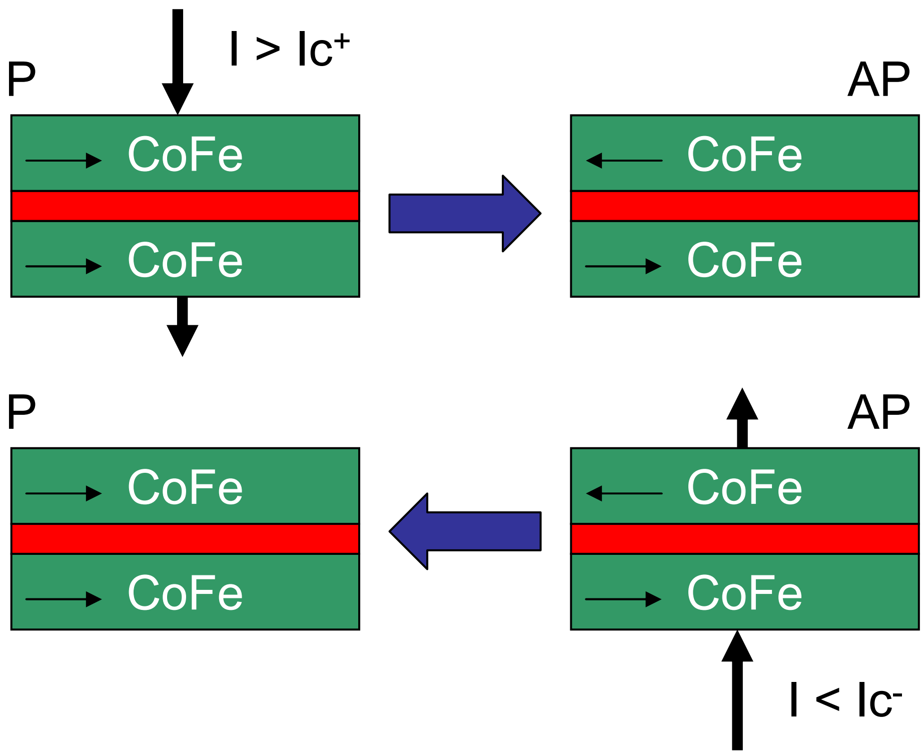


3-input LUT
with non-volatile connfiguration
(will be presented at ICSICT06, Shanghai)



Non volatile FLIP-FLOP
(presented at ICICDT06, Italy)

STT (Spin-Transfer Torque) based MTJ

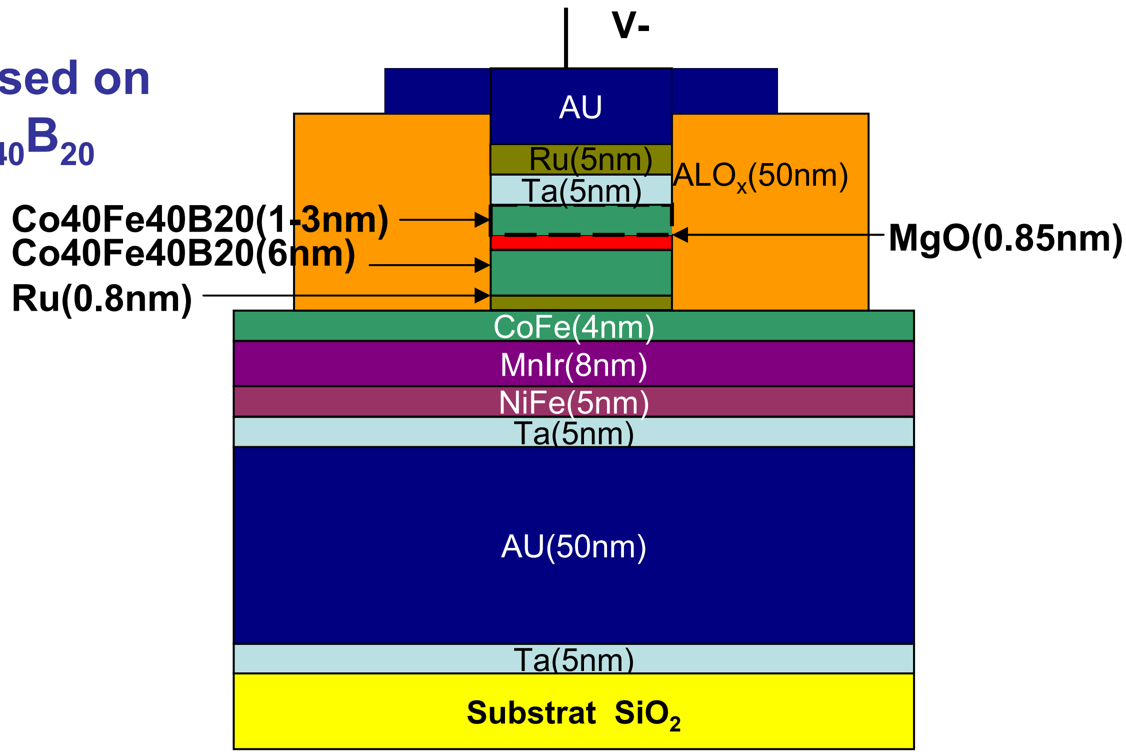


The MTJ state changes :

- **from Parallel (P) to Anti-parallel (AP) if current density I > I_c^+**
- **from AP to P if I < -I_c^-**

STT (Spin-Transfer Torque) based MTJ

The modelized MTJ is based on $Co_{40}Fe_{40}B_{20}$ /MgO/$Co_{40}Fe_{40}B_{20}$



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

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

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

$$E = \frac{M_s \times V \times H_c}{2}$$

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

Hext: the external field: -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 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
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 nm2 ×t)**

STT (Spin-Transfer Torque) based MTJ
2nd eq set : Brinkman conductance model

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

$$G(0) = 3.16\times 10^{10} \times \bar{\varphi}^{1/2} \frac{\exp(-1.025\times d\times \bar{\varphi}^{1/2})}{d}$$

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

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)

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

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

Parameters:

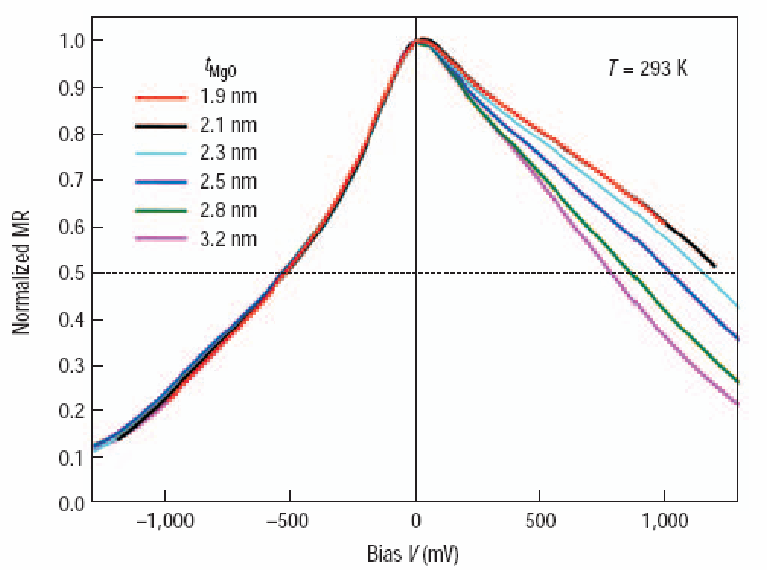
tox: height of barrier in MTJ

surface: surface of the MTJ (rectangle or ellipse)

STT (Spin-Transfer Torque) based MTJ
3rd eq set : TMR bias-voltage dependence model

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

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



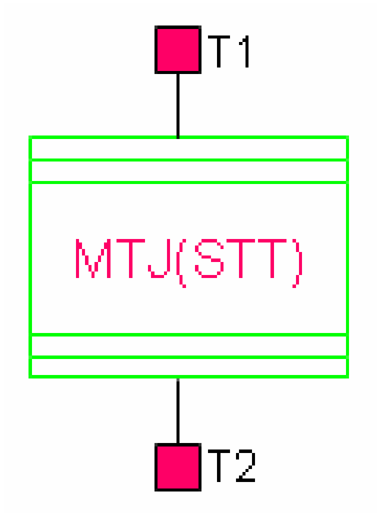
Relation between bias voltage *V* and the normalized MR ratio at room temperature

Yuasa et al, Nature Materials

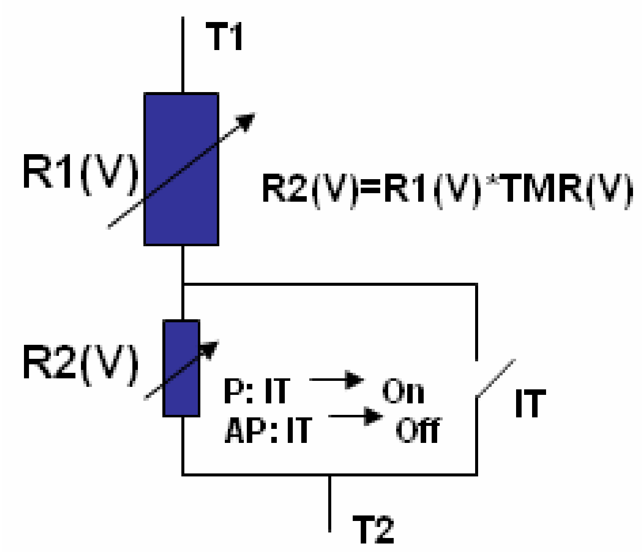
Electrical Macro model developed and Simulations

Simulation Environment:

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

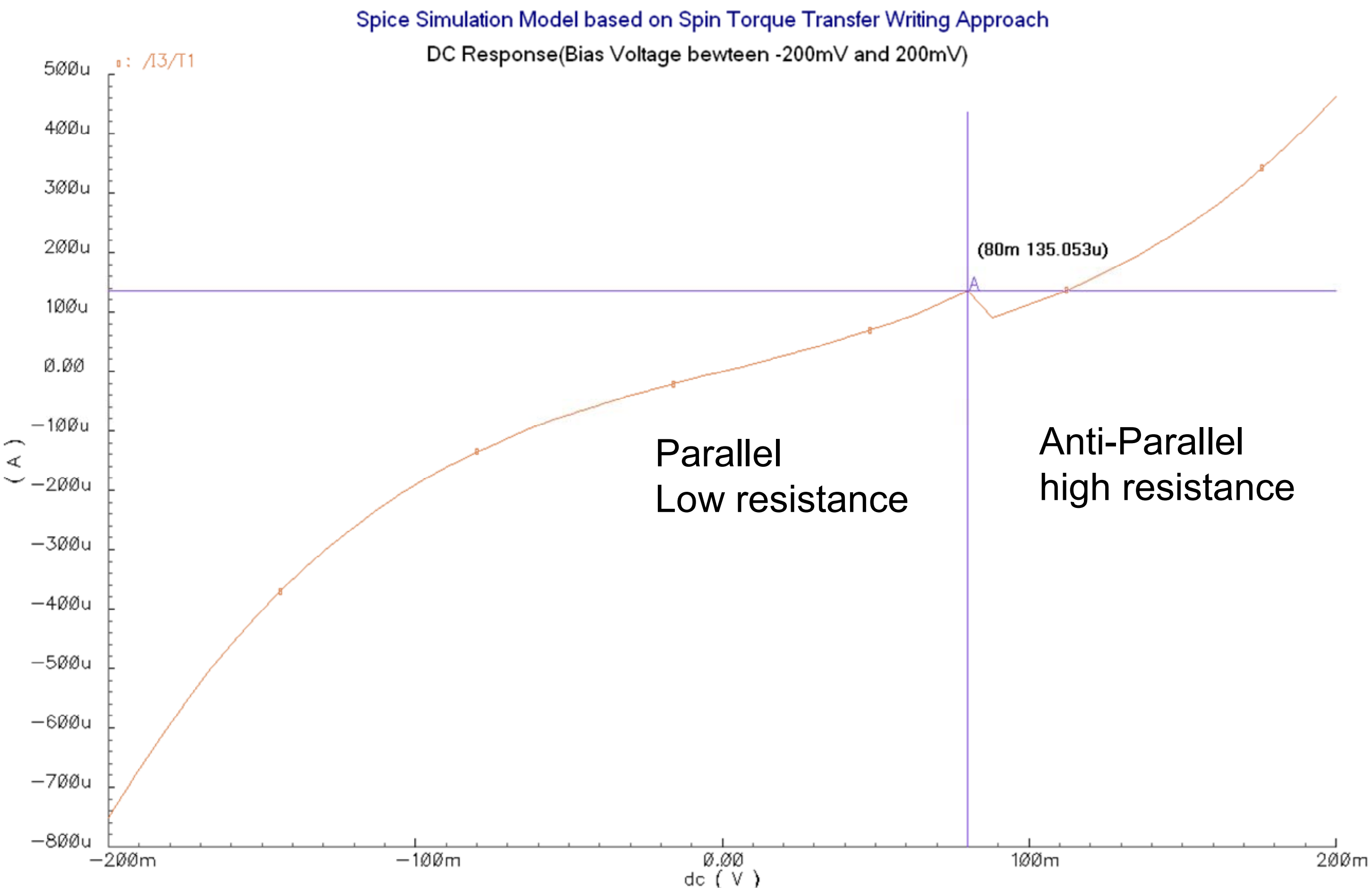


Simulation model symbol



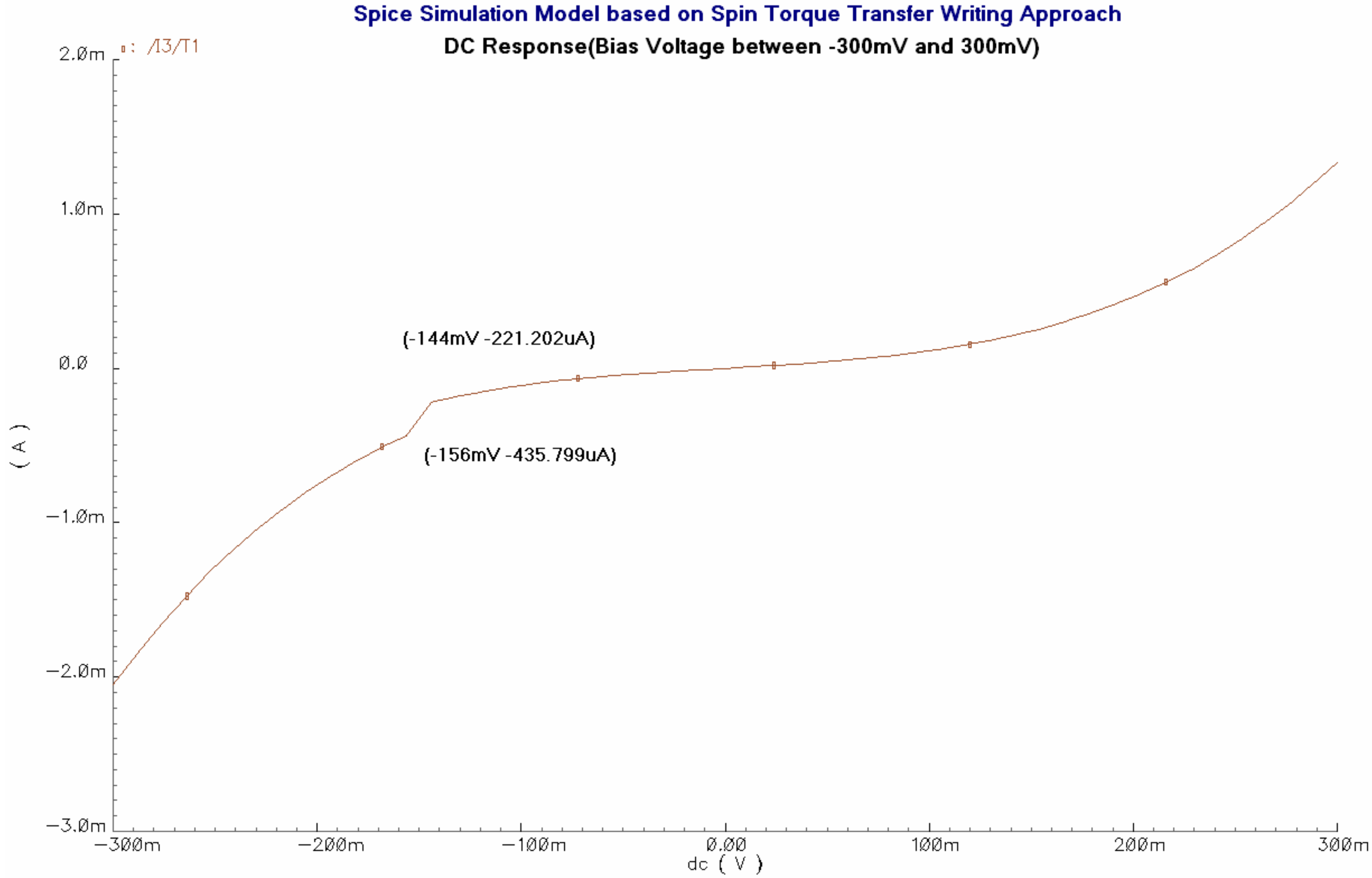
Resistance equivalent circuit

Electrical Macro model developed and Simulations



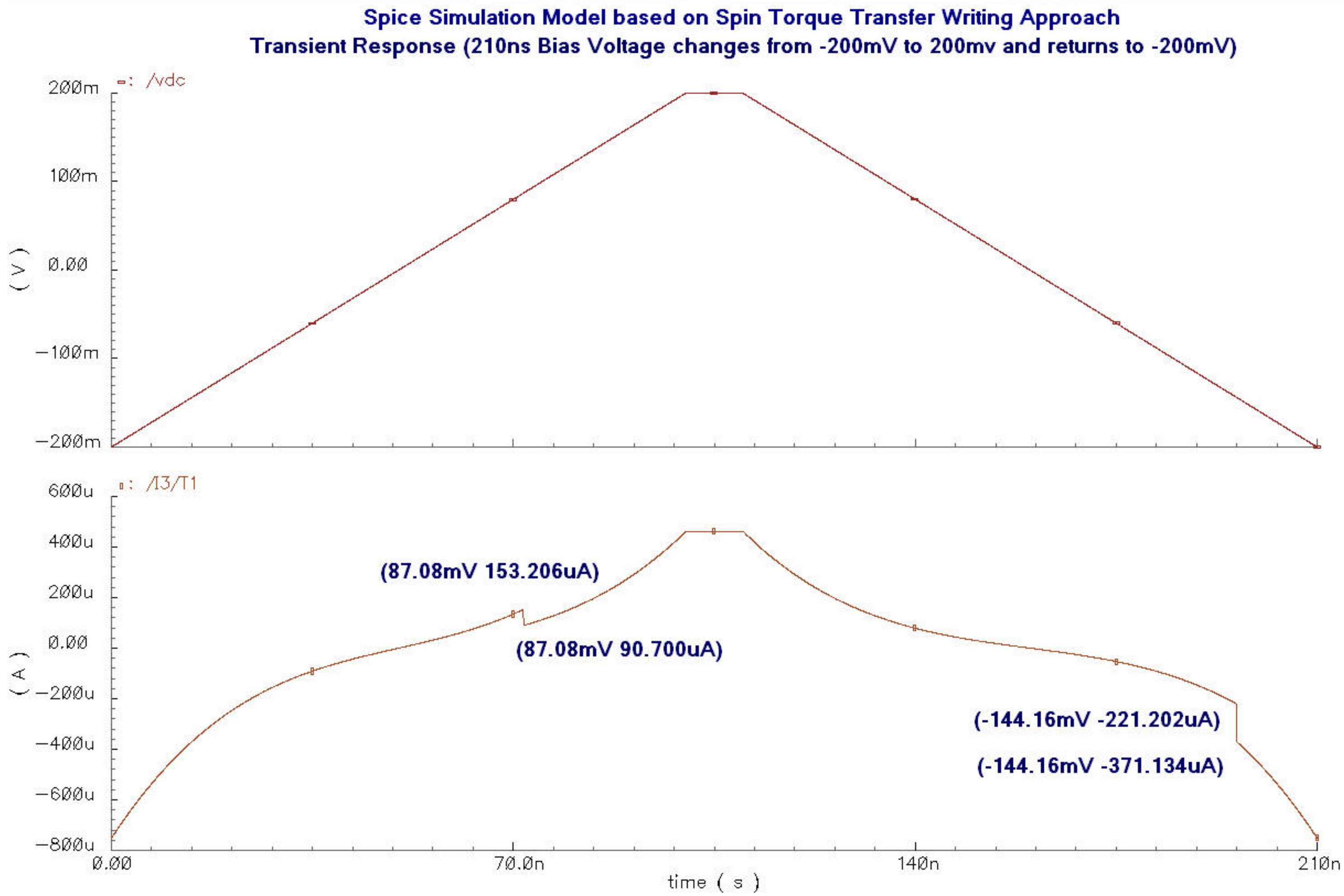
MTJ DC simulation :
the threshold current is about 135 uA
and the threshold voltage is about 80mV

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



MTJ transient simulation :
the threshold current is about
153uA for parallel and -221uA 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