Spintronic Technology For Energy-Efficient In Memory Computing

Part 3 – Magnetic Tunnel Junction

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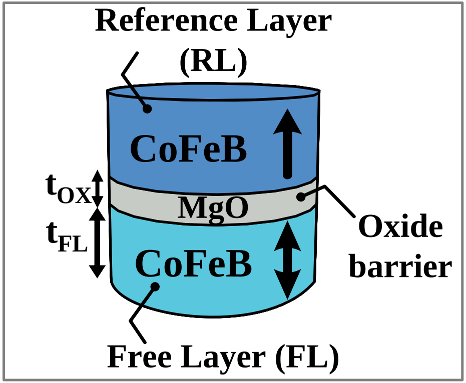
Lecture Outline

1. Device Structure and Working Principle of MTJ
2. MTJ Modeling
3. Analytical Compact Model for nanoscaled perpendicular MTJs
4. MTJ within Circuit Design Flow
5. Summary

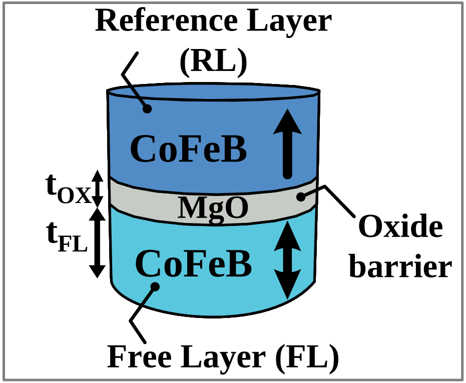
Basic Device Structure of MTJ

- Composed of at least two ferromagnetic layers: RL and FL
- FM layers commonly built with a CoFeB material
- Barrier usually constructed with MgO
- Resistance states can be high or low based on the magnetization orientation



Basic Device Structure of MTJ

- The resistance states can be high (antiparallel orientation) or low (parallel orientation), based on the relative orientation of magnetization of the RL and FL.
  - R_P or R_L
  - R_{AP} or R_H
- The MTJ structure fulfills the three basic memory requirements
  - Read
  - Write
  - Data storage



Magnetoresistive Effect for Reading

- Three different types of MR effects have been studied:
  1. Anisotropic MagnetoResistance (AMR)
  2. Giant MagnetoResistance (GMR)
  3. **Tunnel MagnetoResistance (TMR)**
- MTJ exploits the tunnel magneto resistance (TMR) phenomenon

$$TMR = \left(\frac{R_{AP} - R_P}{R_P}\right) \cdot 100\%$$

- TMR exhibits the highest MR due to the presence of MgO crystal as an insulator

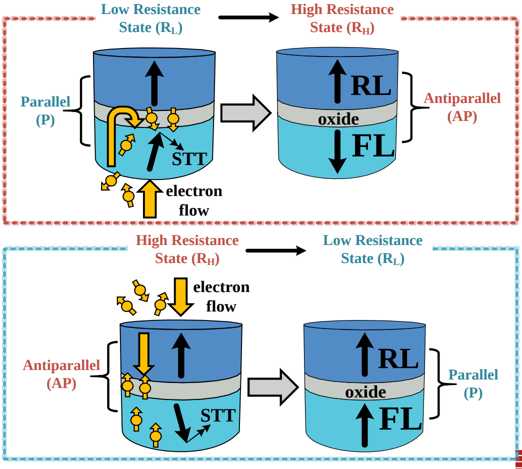
Magnetoresistive (MR) effect

A change in electrical resistance is caused by a change in the applied magnetic field

- **The higher the TMR, the better**. However, it depends on the application
  - Stand-alone memories demand TMR values as high as 300%
  - Embedded memory applications require TMR of around 200%

Spin-Transfer Torque for Writing

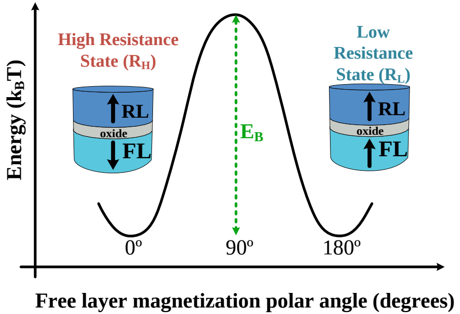
- The write operation of MTJ devices is based on the STT phenomenon
- **Two resistance states** are possible due to the presence of the **oxide barrier**
- **Switching transitions** are performed by injecting a **current greater** than the **critical switching current** of the MTJ
- The direction of the injected current causes the device switching
- Remember: when electrons are not polarized by RL, higher currents are needed.



MTJ Resistance State and Energy Barrier – Data Retention

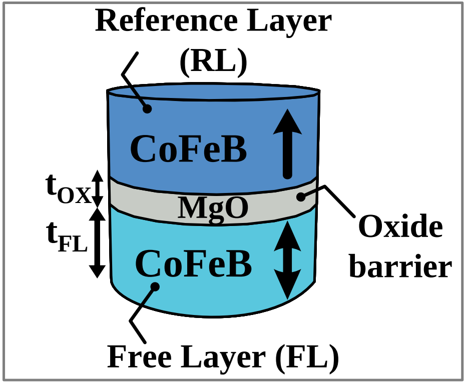
- The MTJ **readout** and **data storage** are **related to the resistance** of the MTJ device
- MTJ must be **stable** enough to maintain is data (i.e., the magnetization state)
- The **energy barrier** (E_b) prevents switching between the two possible states
  - It follows the thermal stability factor expression: $\Delta = \frac{E_b}{k_b\,T}$
    k_b: Boltzmann constant
    T: Operating temperature K

- Δ indicates the difficulty of switching between the two stable magnetization states at a given temperature
- $\Delta > 45$ is required to assure a data retention time of 10 years



Ferromagnetic Material: In-Plane Magnetic Anisotropy and Perpendicular Magnetic Anisotropy

- **The E_b of the MTJ is related to: type of magnetic anisotropy energy of FM material that provides nonvolatile data retention.**
- Two types of magnetic anisotropy energy
  - in-plane magnetic anisotropy (IMA)
  - perpendicular MA (PMA)
- **PMA** is used to achieve **high integration density** and a **"low" switching critical current**
- PMA occurs at the interface between the MgO and CoFeB layers



MTJ Issues

1. Write Operation
   - The switching (STT) of the MTJ is an stochastic process
   - Thermal fluctuations can cause changes in the magnetic moment of the material, affecting the switching process
   - Write failure: the FL switching depends on the applied pulse and its duration
2. Read Operation
   - Read failures: The TMR is not high enough to differentiate between R_{AP} and R_P orientations.

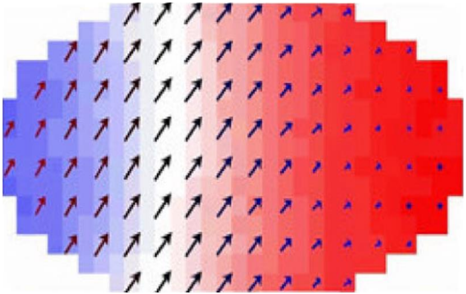
$$TMR = \left(\frac{R_{AP} - R_P}{R_P}\right) \cdot 100\%$$

   - Read disturbance: an unwanted switching may occur during the read operation.
3. Retention Retention
   - The magnetization of the FL can switch even without an injected current due to the influence of the thermal field.

$$\Delta = \frac{E_b}{k_b T}$$

Micromagnetic Modeling

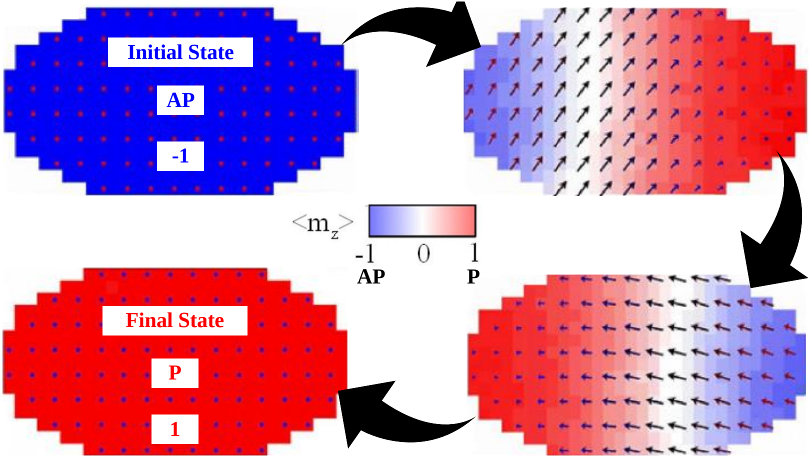
- A more detailed method of simulating magnetization dynamics that takes into account the **microscopic details** of the **magnetic material**
- Requires a larger number of **cells** to **represent the magnetization distribution** in the material
- Can capture more complex phenomena, such as domain wall motion, magnetic noise, and thermal effects
  - Uses non-linear partial differential equations



Source: Francesco Cutugno, et. al. (2021) "Field-Free Magnetic Tunnel Junction for Logic Operations Based on Voltage-Controlled Magnetic Anisotropy". IEEE MAGNETICS LETTERS.

Micromagnetic Modeling

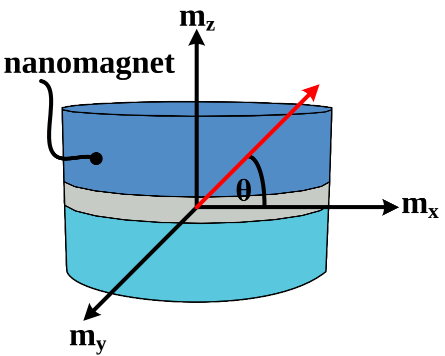
- Magnetization snapshots for different times



Source: Francesco Cutugno, et. al. (2021) "Field-Free Magnetic Tunnel Junction for Logic Operations Based on Voltage-Controlled Magnetic Anisotropy". IEEE MAGNETICS LETTERS.

Macrospin Modeling

- A **simplified method** of simulating **magnetization dynamics** in magnetic materials
- Represents magnetization by a **single macrospin**
- Provides a **fast and efficient** way of simulating the effects of spin transfer torque on the magnetization dynamics of the magnetic layers in STT-MTJs
- Can **analyze** the **critical current** required to induce magnetization switching and the spin transfer torque generated during the switching



Macrospin vs. Micromagnetic Modeling: Advantages and Limitations

Macrospin Modeling

- Advantages:
  - Fast and efficient, useful for designing and optimizing STT-MTJ-based devices
- Limmitations:
  - May not capture some of the detailed behavior of the material

Micromagnetic Modeling

- Advantages:
  - More accurate, can capture complex behavior of the material
- Limmitations:
  - Computationally expensive, may require more time and resources

Macrospin modeling is more simplified and provides a **good approximation** that can guide the design and optimization of STT-MTJ-based devices

Choosing the appropriate modeling approach depends on the specific research question, the available resources, and the desired level of accuracy

Macrospin Model: Techniques

- There are several techniques for Classical Macrospin modeling:
  - Numerical simulations using the Landau-Lifshitz-Gilbert (LLG) equation
  - **Analytical methods: analytical Macrospin model**
  - Semi-analytical methods such as the Modified Landau-Lifshitz-Bloch (MLLB) equation

- Analytical Macrospin Modeling
  - Fast runtime ☺
  - Easy to calibrate with experimental data ☺
  - Not so accurate in the sub-nanosecond range ☹

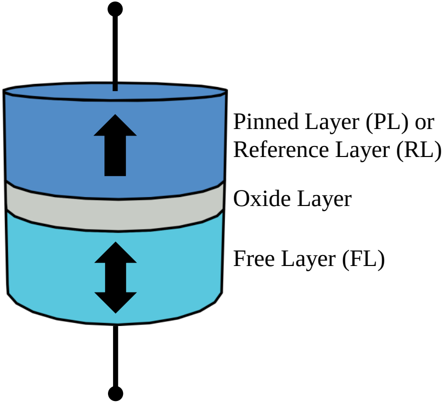
From here we will briefly describe an analytical compact developed in collaboration between different research groups in Italy

Analytical Macrospin Compact Model

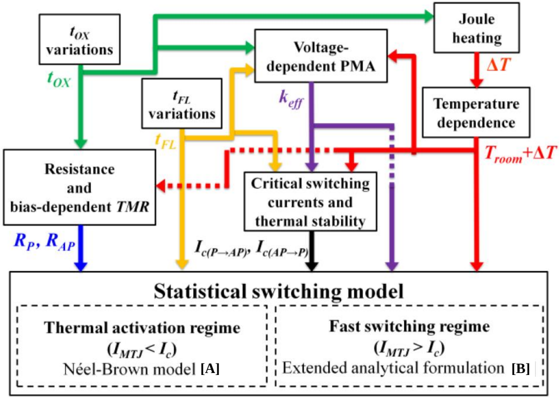
- The model was developed and published in IEEE Transactions Journal
  - **De Rose, R., et al. ”A compact model with spin-polarization asymmetry for nanoscaled perpendicular MTJs.” IEEE Transactions on Electron Devices 64.10 (2017): 4346-4353.**
- Additional resources:
  - SpinLib, Beihang University
  - NanoHub, Purdue University
  - SPICE-compatible compact model: Panagopoulos, Georgios D., Charles Augustine, and Kaushik Roy. ”Physics-based SPICE-compatible compact model for simulating hybrid MTJ/CMOS circuits.” IEEE Transactions on Electron Devices 60.9 (2013): 2808-2814.

Compact Model Overview

- Effects considered in the compact model:
  - Resistance and Bias Dependent TMR
  - Critical Switching Currents and Thermal Stability
  - Statistical Switching Model
  - Voltage Dependent PMA
  - Temperature Dependence and Joule Heating
  - t_{OX} and t_{FL} Variations



- In contrast to the model published by De Rose, et al. The effect of temperature has been modified. Temperature-dependent equations are mainly based on the following works:
    - Kou, X., et al. Applied Physics Letters. 2006
    - Zhang, Y., et al. IEEE TED. 2015



Source: De Rose, R., et al. IEEE TED. 2017

[A] Zhang, Yue, et al. IEEE TMAG. 2013
[B] Siracusano, G., et al. arXiv preprint. 2017

Preliminaries (Variables)

Temperature-dependence & resistance and TMR variables

- Temperature-dependent variables:
  - T_{eff} $[\mathrm{K}]$: effective temperature of the FL
  - M_S $[\mathrm{A/m}]$: saturation magnetization
  - k_i $[\mathrm{J/m^2}]$: interfacial PMA constant
  - ξ $[\mathrm{J/(V\ m)}]$: magnetoelectric coefficient
  - P []: spin polarization
- Parameters for temperature dependence:
  - T^* $[\mathrm{K}]$: fitting parameter
  - M_{S0} $[\mathrm{A/m}]$: sat. mag. at $0\,\mathrm{K}$
  - k_{i0} $[\mathrm{J/m^2}]$: interfacial PMA constant at $0\,\mathrm{K}$
  - ξ_0 $[\mathrm{J/(V\ m)}]$: VCMA coef. at $0\,\mathrm{K}$
  - P_0 []: spin polarization at $0\,\mathrm{K}$
- Variables for resistance and TMR model
  - G_0 $[\mathrm{S}]$: fitting variable for conductance
  - λ_G []: variable to compute conductance prefactor for direct elastic tunneling
  - G_T $[\mathrm{S}]$: conductance prefactor for direct elastic tunneling
  - G_{si} $[\mathrm{S}]$: inelastic spin-independent conductance
  - R_P $[\Omega]$: resistance in P state
  - R_{AP} $[\Omega]$: resistance in AP state
  - $TMR_{T,0}$ []: temperature-dependent TMR at zero voltage bias
  - $TMR_{T,V}$ []: temperature-dependent TMR with voltage bias effect

Resistance and TMR Model

- Parameters:
  - $\Phi_B = 0.4$ [eV]: energy barrier height for MgO
  - $V_h = 0.5$ [V]: voltage bias when the TMR is $1/2 \cdot TMR_{T,0}$. (experimental value for MgO)
  - $S = \times 10^{-12}$ []: spin independent conductance factor for oxide barrier
  - F []: fitting factor for RA product and hence MTJ resistance
- Initial calculations for resistance and TMR model

$$G_0 = 3.16 \times 10^{10} \cdot \sqrt{\Phi_B} \cdot \exp(-1.025 \cdot t_{OX} \cdot 1 \times 10^{10} \cdot \sqrt{\Phi_B}) \cdot \mathrm{Area} \cdot 10^4 \cdot \mathrm{F}/(t_{OX} \cdot 10^{10})$$

$$\lambda_G = 1.387 \cdot 10^{-4} \cdot t_{OX} \cdot 10^{10} / \sqrt{\Phi_B}$$

Resistance and TMR Model (Cont.)

$$P = P_0 \cdot (1 - (2 \times 10^{-5} \cdot T_{eff}^{1.5}))$$

$$TMR_{T,0} = (2 \cdot P \cdot P)/((1 - P \cdot P) + (G_{si}/G_T))$$

$$G_T = G_0 \cdot \lambda_G \cdot T_{eff} / \sin(\lambda_G \cdot T_{eff})$$

$$TMR_{T,V} = TMR_{T,0}/(1 + (V_b \cdot V_b)/(V_h \cdot V_h))$$

$$G_{si} = S \cdot T_{eff}^{1.33}$$

- Now we can define the MTJ resistance and TMR:

$$R_{AP} = R_P \cdot (1 + TMR_{T,V})$$

$$R_P = 1/(G_T \cdot (1 + P \cdot P) + G_{si})$$

Preliminaries (Variables)

Switching model

- Variables for switching model:
  - k_{eff} []: normalized effective PMA constant with temperature dependence
  - N_z []: normalized demagnetizing factor along z-axis
  - N_{perp} []: normalized demagnetizing factor along x- and y-axis
  - β_N []: variable to compute normalized demagnetizing factors
  - c_P []: variable to model the asymmetry of the spin-torque (= P^2)
  - β_P []: normalized critical current for $P \rightarrow AP$ switching
  - haz []: normalized external field
  - β_{AP} []: normalized critical current for $AP \rightarrow P$ switching
  - I_{cP} [A]: critical current for $P \rightarrow AP$ switching
  - I_{cAP} [A]:critical current for $AP \rightarrow P$ switching
  - Δ []: thermal stability factor
  - θ [rad]: initial tilting angle of the FL magnetization with respect to z-axis
  - m_{z0} []: initial state of the FL magnetization
  - τ_{sw} []: normalized switching time
  - t_{write} [s]: switching time

Critical Switching Current Model (Cont.)

$$c_P = P \cdot P$$

$$M_S = M_{S0} \cdot (1 - (T_{eff}/T^*)^{1.5})$$

$$k_i = k_{i0} \cdot (M_S/M_{S0})^{2.18}$$

$$\xi = \xi_0 \cdot (M_S/M_{S0})^{2.83}$$

$$\beta_N = 2r/t_{fl}$$

$$N_z = (\beta_N \cdot \beta_N/(\beta_N \cdot \beta_N - 1)) \cdot \left(1 - \frac{arcsin((\beta_N \cdot \beta_N - 1)^{0.5}/\beta_N)}{(\beta_N \cdot \beta_N - 1)^{0.5}}\right)$$

$$N_{perp} = (1 - N_z)/2$$

Critical Switching Current Model (Cont.)

Voltage-dependent interfacial PMA

- Voltage-dependent PMA model (normalized effective PMA constant):
  - without voltage-dependent PMA

$$k_{eff} = (2 \cdot k_i / (\mu_0 \cdot M_S \cdot M_S \cdot t_{fl})) - (N_z - N_{perp})$$

  - with voltage-dependent PMA

$$k_{eff} = (2 \cdot k_i / (\mu_0 \cdot M_S \cdot M_S \cdot t_{fl})) - (N_z - N_{perp}) - (2 \cdot \xi \cdot V_b / (\mu_0 \cdot M_S \cdot M_S \cdot t_{OX} \cdot t_{fl}))$$

- Thermal stability factor

$$\Delta = \frac{\mu_0 \cdot M_S \cdot M_S \cdot t_{fl} \cdot Area \cdot k_{eff}}{2 \cdot k_b \cdot T_{eff}}$$

Critical Switching Current Model (Cont.)

Critical switching currents

- Critical switching currents follows:

$$\beta_P = \alpha \cdot (1 + c_P) \cdot (k_{eff} + haz)$$

$$\beta_{AP} = \alpha \cdot (1 - c_P) \cdot (k_{eff} + haz)$$

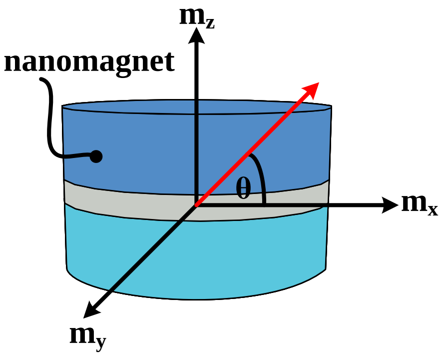
$$I_{cP} = \beta_P \cdot e \cdot \gamma \cdot \mu_0 \cdot M_S \cdot M_S \cdot t_{fl} \cdot Area/(\mu_b \cdot 2 \cdot P \cdot g)$$

$$I_{cAP} = \beta_{AP} \cdot e \cdot \gamma \cdot \mu_0 \cdot M_S \cdot M_S \cdot t_{fl} \cdot Area/(\mu_b \cdot 2 \cdot P \cdot g)$$

  - γ [Hz/T]: gyromagnetic constant
  - α []: Gilbert damping coefficient
  - g []: Lande factor

STT switching (fast switching regime)

- The switching time of the MTJ under the condition of MTJ current (I_{MTJ}) greater than the critical switching current of the MTJ (I_c)
- Two possible switching transitions
    - $P \rightarrow AP$ (This switching time expression will be discussed hereafter)
    - $AP \rightarrow P$
    - The initial magnetization state (m_{z0}) depends on the direction of the FL magnetization orientation relative to the reference layer



STT switching (fast switching regime)

- Variables for the calculation of the switching time (P$\rightarrow$AP, P is the initial state)

$$C1 = \sqrt{4 \cdot \epsilon \cdot c_P \cdot k_{eff} - 2 \cdot haz \cdot c_P \cdot k_{eff} + (haz \cdot c_P) \cdot (haz \cdot c_P) + k_{eff} \cdot k_{eff}}$$

$$C2 = arctanh((k_{eff} + 2 \cdot k_{eff} \cdot c_P \cdot m_{z0} + haz \cdot c_P)/C1)$$

$$C3 = arctanh((k_{eff} + 2 \cdot k_{eff} \cdot c_P \cdot m_{zfP} + haz \cdot c_P)/C1)$$

$$C4 = \ln |k_{eff} \cdot m_{zfP} + k_{eff} \cdot m_{zfP} \cdot m_{zfP} \cdot c_P + haz + haz \cdot c_P \cdot m_{zfP} - \epsilon|$$

$$C5 = \ln |(k_{eff} \cdot m_{z0} + k_{eff} \cdot m_{z0} \cdot m_{z0} \cdot c_P + haz + haz \cdot c_P \cdot m_{z0} - \epsilon|$$

- $\epsilon = \beta/\alpha$
- $\beta = I_{MTJ} \cdot 2 \cdot P \cdot g \cdot \mu_b/(e \cdot \gamma \cdot \mu_0 \cdot M_S \cdot M_S \cdot t_{fl} \cdot Area)$
- $m_{zfP} = -0.9$ is the final state of the magnetization for P to AP switching

STT switching (fast switching regime)

- Formula for the normalized switching (P to AP) time:

$$\tau_{sw} = -\frac{1}{2\cdot\alpha}\cdot\frac{Num}{Den}$$

$$\begin{aligned}
Num =\; & k_{eff}\cdot C4\cdot C1 - k_{eff}\cdot C5\cdot C1 - \ln(1+m_{zfP})\cdot C1\cdot haz + \ln(1+m_{zfP})\cdot C1\cdot\epsilon - \ln|m_{z0}-1|\cdot C1\cdot haz\\
& - 2\cdot C3\cdot k_{eff}\cdot k_{eff} - 2\cdot C3\cdot\epsilon\cdot c_P\cdot c_P\cdot haz - 2\cdot C3\cdot haz\cdot c_P\cdot c_P\cdot c_P\cdot k_{eff} - 6\cdot C3\cdot\epsilon\cdot c_P\cdot k_{eff}\\
& + 2\cdot C3\cdot haz\cdot c_P\cdot k_{eff} + 2\cdot C3\cdot k_{eff}\cdot k_{eff}\cdot c_P\cdot c_P - \ln(1+m_{zfP})\cdot C1\cdot k_{eff} + 2\cdot C2\cdot haz\cdot c_P\cdot c_P\cdot c_P\cdot k_{eff}\\
& - 2\cdot C2\cdot haz\cdot c_P\cdot k_{eff} + 6\cdot C2\cdot\epsilon\cdot c_P\cdot k_{eff} + 2\cdot C2\cdot\epsilon\cdot c_P\cdot c_P\cdot haz + 2\cdot C2\cdot k_{eff}\cdot k_{eff}\\
& - 2\cdot C2\cdot k_{eff}\cdot k_{eff}\cdot c_P\cdot c_P + \ln(abs(m_{z0}-1))\cdot c_P\cdot c_P\cdot C1\cdot haz - \ln(abs(m_{z0}-1))\cdot c_P\cdot c_P\cdot C1\cdot k_{eff}\\
& + \ln(abs(m_{z0}-1))\cdot c_P\cdot C1\cdot\epsilon + \ln(1+m_{zfP})\cdot c_P\cdot c_P\cdot C1\cdot k_{eff} + \ln(1+m_{zfP})\cdot c_P\cdot c_P\cdot C1\cdot haz\\
& - \ln(1+m_{zfP})\cdot c_P\cdot C1\cdot\epsilon - \ln(1+m_{z0})\cdot c_P\cdot c_P\cdot C1\cdot k_{eff} - \ln(1+m_{z0})\cdot c_P\cdot c_P\cdot C1\cdot haz\\
& + \ln(1+m_{z0})\cdot c_P\cdot C1\cdot\epsilon - \ln(abs(m_{zfP}-1))\cdot c_P\cdot c_P\cdot C1\cdot haz + \ln(abs(m_{zfP}-1))\cdot c_P\cdot c_P\cdot C1\cdot k_{eff}\\
& - \ln(abs(m_{zfP}-1))\cdot c_P\cdot C1\cdot\epsilon + k_{eff}\cdot c_P\cdot c_P\cdot C5\cdot C1 - c_P\cdot C5\cdot\epsilon\cdot C1 - k_{eff}\cdot c_P\cdot c_P\cdot C4\cdot C1\\
& + c_P\cdot C4\cdot\epsilon\cdot C1 + \ln(1+m_{z0})\cdot C1\cdot haz - \ln(1+m_{z0})\cdot C1\cdot\epsilon + \ln(1+m_{z0})\cdot C1\cdot k_{eff}\\
& + \ln|m_{zfP}-1|\cdot C1\cdot haz - \ln|m_{zfP}-1|\cdot C1\cdot k_{eff} - \ln|m_{zfP}-1|\cdot C1\cdot\epsilon\\
& + \ln|m_{z0}-1|\cdot C1\cdot\epsilon + \ln|m_{z0}-1|\cdot C1\cdot k_{eff}
\end{aligned}$$

$$\begin{aligned}
Den =\; & (haz + k_{eff}\cdot c_P - \epsilon + haz\cdot c_P + k_{eff})\\
& \cdot (haz - k_{eff} - \epsilon - haz\cdot c_P + k_{eff}\cdot c_P)\cdot C1
\end{aligned}$$

STT switching (fast switching regime)

- Denormalizing the switching time

$$t_{write} = \tau_{sw} / (\gamma \cdot \mu_0 \cdot M_S)$$

- **Similar expressions (HERE) correspond to the $AP \rightarrow P$ switching transition**

- $P \rightarrow AP$
  - FL initial tilting angle:

$$\theta = \sqrt{- \ln (1 - WER) / \Delta}$$

  - FL final state of the magnetization:

$$m_{zfP} = -0.9$$

- $AP \rightarrow P$
  - FL initial tilting angle:

$$\theta = \pi - \sqrt{- \ln (1 - WER) / \Delta}$$

  - FL final state of the magnetization:

$$m_{zfAP} = +0.9$$

Go to WER

MTJ Read and Write errors

- During the MTJ write and read operations, the write and read currents strongly affect the write and read error rates, respectively.
  - Write errors: when the device is unable to write new data onto the MTJ
  - Read errors: when the device is unable to read the stored data of the MTJ
- To ensure error rates close to zero:
  - **Write current** has to be **high** enough
  - **Read current** has to be **low** enough
- Typically, error rates span from 10^{-6} to 10^{-11}

Write-Error-Rate (WER)

It is defined as the probability of No-switching during a write event

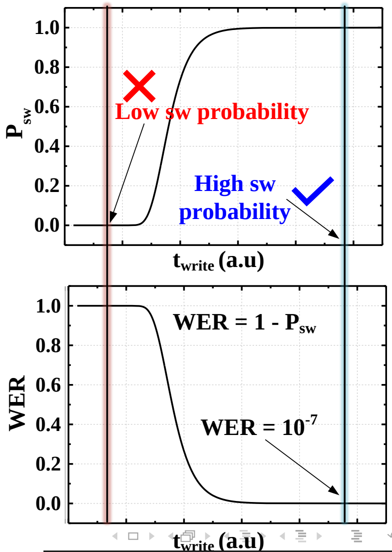
- **Write failures** can occur when the **amplitude and/or duration of the write pulse** used to switch the orientation of the free layer magnetization is **insufficient**.
- The I_{write} has to be high enough to ensure a low WER.
- **MTJ switching is stochastic** $\rightarrow$ We can obtain the Cumulative Distribution Function (CDF) of the switching time
  - CDF provides a complete picture of the distribution of the switching time by showing the probability of all possible values of the switching time.
  - useful in statistical analysis and modeling of MTJ devices

Write-Error-Rate (WER)

- MTJ switching is stochastic
  - For a given I_{write} and a write pulse (t_{write}), we have a probability of switching (P_{sw})
- The WER can be expressed as

$$WER = 1 - P_{sw}$$

- Note: the P_{sw} is the Cumulative Distribution Function (CDF)



Write-Error-Rate (WER)

- Recalling the FL initial tilting angle (θ) in regard to the STT switching, we can obtain the write time (t_{write}) required to achieve a WER. Go to initial tilting angle
- How? the θ is calculated as follows
  1. From the probability distribution function (PDF) of the switching time (τ_{sw}), we get the CDF

$$PDF(\tau_{sw,P\to AP}) = 2\Delta exp\left(-\Delta arccos^2\left(g^{-1}(\tau_{sw,P\to AP})\right)\right) \cdot \left|\alpha\left(k_{eff}g^{-1}(\tau_{sw,P\to AP}) - \beta/\alpha\left(1 + c_P g^{-1}(\tau_{sw,P\to AP})\right)^{-1}\right) \cdot \left(1 - \left(g^{-1}(\tau_{sw,P\to AP})\right)^{-1}\right)\right|$$

- **Note: Several probability distributions have been proposed for the fast switching regime. The one mentioned in this lecture fits well for our model.**

Write-Error-Rate (WER)

- Recalling the FL initial tilting angle (θ) in regard to the STT switching, we can obtain the write time (t_{write}) required to achieve a WER. ◂ Go to initial tilting angle
- How?... the θ is calculated as follows
  1. From the probability distribution function (PDF) of the switching time (τ_{sw}), we get the CDF

$$PDF(\tau_{sw,P\to AP}) = 2\Delta exp\left(-\Delta arccos^2\left(g^{-1}(\tau_{sw,P\to AP})\right)\right) \cdot \left|\alpha\left(k_{eff}g^{-1}(\tau_{sw,P\to AP}) - \beta/\alpha\left(1 + c_P g^{-1}(\tau_{sw,P\to AP})\right)^{-1}\right) \cdot \left(1 - \left(g^{-1}(\tau_{sw,P\to AP})\right)^{-1}\right)\right|$$

$$CDF(\tau_{sw,P\to AP}) = exp\left(-\Delta arccos^2\left(g^{-1}(\tau_{sw,P\to AP})\right)\right)$$

Write-Error-Rate (WER)

- Recalling the FL initial tilting angle (θ) in regard to the STT switching, we can obtain the write time (t_{write}) required to achieve a WER. Go to initial tilting angle
- How?... the θ is calculated as follows
  2. CDF and switching time

$$CDF(\tau_{sw,P\to AP}) = exp\left(-\Delta arccos^2\left(g^{-1}(\tau_{sw,P\to AP})\right)\right)$$

$$\tau_{sw,P\to AP} = g(m_{z0}) \to g^{-1}(\tau_{sw,P\to AP}) = m_{z0}$$

$$\therefore arccos(g^{-1}(\tau_{sw,P\to AP})) = arccos(m_{z0})$$

Write-Error-Rate (WER)

- Recalling the FL initial tilting angle (θ) in regard to the STT switching, we can obtain the write time (t_{write}) required to achieve a WER. ◂ Go to initial tilting angle
- How?... the θ is calculated as follows
  3. Rewriting the CDF in terms of θ
     Remember: $m_{z0} = cos(\theta)$

$$\theta = arccos(m_{z0}) = arccos(g^{-1}(\tau_{sw,P\rightarrow AP}))$$

$$\therefore CDF(\tau_{sw,P\rightarrow AP})) = exp(-\Delta\theta^2)$$

Write-Error-Rate (WER)

- Recalling the FL initial tilting angle (θ) in regard to the STT switching, we can obtain the write time (t_{write}) required to achieve a WER. Go to initial tilting angle
- How?... the θ is calculated as follows
  4. FL tilting angle, θ, as a function of the WER

$$WER(\tau_{sw,P\rightarrow AP})) = 1 - CDF(\tau_{sw,P\rightarrow AP})) = 1 - exp(-\Delta\theta^2)$$

$$\theta(WER) = \sqrt{-\ln\left(1 - WER\right)/\Delta}$$

Read Disturbance Rate (RDR)

Read Disturbance Rate (RDR)

It is defined as the probability to disturb or flip (i.e., unwanted switching) the stored data during a reading event

- Read failures can occur when the read current (I_{read}) is close to the critical switching current of the MTJ device.
- The I_{read} has to be low enough to avoid unwanted switching of the FL magnetization, and ensure a low RDR
- RDR is defined as:

$$RDR = 1 - exp\left\{-\frac{t_{read}}{\tau_0}exp\left(-\Delta\left(1-\frac{I_{read}}{I_{c0}}\right)\right)\right\}$$

Read Disturbance Rate (RDR)

$$RDR = 1 - exp\left\{-\frac{t_{read}}{\tau_0}exp\left(-\Delta\left(1-\frac{I_{read}}{I_{c0}}\right)\right)\right\} \quad (1)$$

- t_{read} $[\mathrm{s}]$: read pulse width
- τ_0 $[\mathrm{s}]$: attempt period (typically around 1 ns)
- I_{c0} $[\mathrm{A}]$: refers to that associated with the $P \rightarrow AP$ (or $AP \rightarrow P$) transition
- Note:
  - Lower the t_{read}, lower the RDR
  - Lower the I_{read}/I_{c0}, lower the RDR
  - Higher the Δ, lower the RDR
- **Generally, we need to set the I_{read}. From (1), we can estimate the I_{read}/I_{c0} for a target RDR and given Δ, t_{read}**

$$\frac{I_{read}}{I_{c0}} = 1 + \frac{\ln\left[-(\tau_0/t_{read})\cdot\ln(1-RDR)\right]}{\Delta}$$

Retention Failure Rate (RFR)

Temperature Effect on the Retention Capability

Retention Failure Rate (RFR)

It is defined as the probability of an unwanted bit flipping due to thermal noise also in absence of injected currents

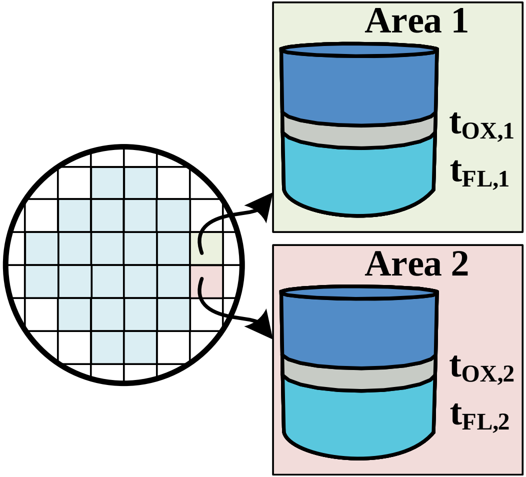
- The retention failure is obtained from *RDR* equation when $I_{read} = 0$

$$RFR = 1 - exp\left\{\frac{t_{retention}}{\tau_0 \cdot exp(\Delta)}\right\}$$

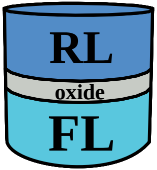
- *RDR* depends on the thermal stability, i.e., Δ

MTJ process variations

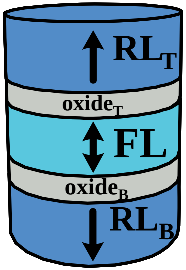
- The analytical compact model takes into account the effect of process variations
  - oxide thickness
  - FL thickness
  - cross-section area
- It is generated *n* samples for the above variables. These follow a normal distribution with that corresponds to a given standard deviation.
- The variations are taken from state-of-the-art physical experiments



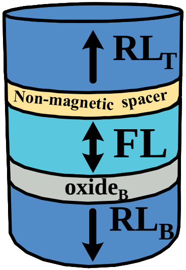
Summary & Advanced STT-MTJ structures



Single-barrier MTJ (SMTJ)



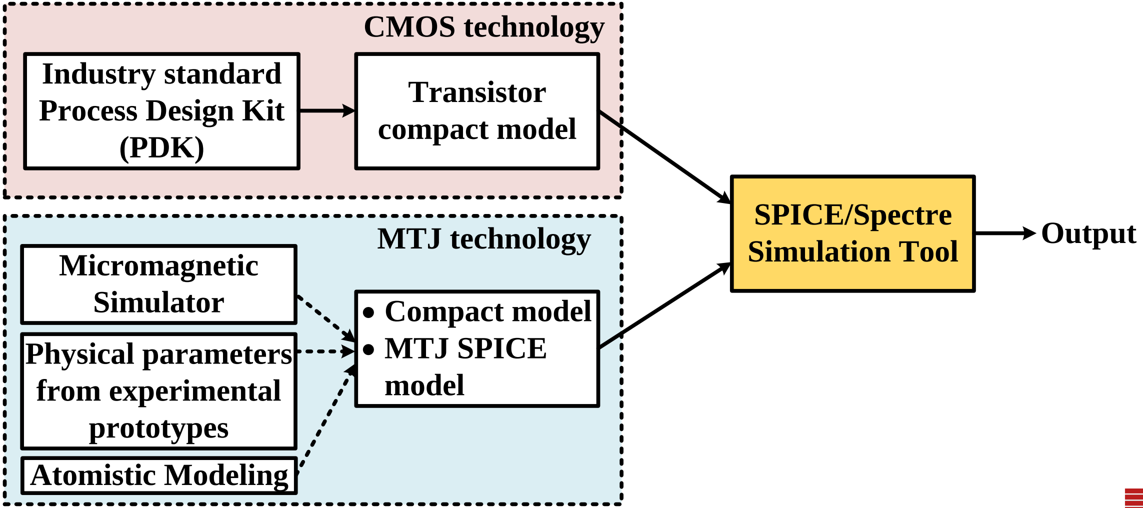
Double-barrier MTJ (DMTJ)



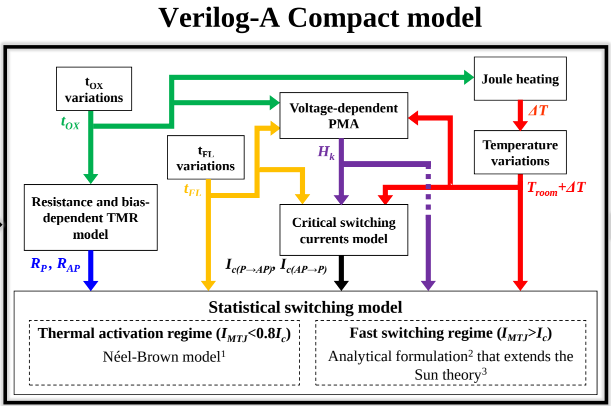
Double Spin-torque MTJ (DS-MTJ)

Source: Compact model SMTJ: De Rose, R., et. al., TED,2017
Source: Compact model DMTJ: De Rose, R., et. al., TNANO, 2019
Source: DS-MTJ: Hu, G., et. al., IEDM, 2021

Overall Circuit Design Flow



INPUTS:
- Experimental data
- Simulation parameters



OUTPUTS:
- MTJ Switching time
- State of the MTJ (parallel or antiparallel)

Summary

- Macrospin model: simulation of magnetization dynamics in magnetic materials that treats the magnetization as a classical vector.
- Macrospin model: good alternative to evaluate MTJ devices and design hybrid CMOS/MTJ circuits
- Different model flavors available in the literature.
- The MTJ devices have write, read, and data retention “issues”/“constraints” that have to been taken into account
- Compact models have to be compatible with circuit design tools
- **The presented analytical compact model consider all the necessary effects to make accurate assessments in hybrid CMOS/MTJ circuit design.**