Manual of compact models for VCMA-driven MTJ

SPINLIB: Model VCMA_MTJ

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Table of contents

I. General Introduction

Compared to memories based on CMOS transistors, STT-MRAMs have zero static power consumption due to the non-volatile property of its basic component Magnetic tunnel junction (MTJ). However, the critical current required for the switching of magnetic resistance state generally range from dozens to a few hundred micro amps, resulting in relatively high dynamic power consumption. Besides, it is necessary to use transistors with relatively large size to provide sufficient current drive capability for STT-MRAM, which hinders the technology node scaling of STT-MRAM.

In recent years, Voltage-controlled Magnetic Anisotropy (VCMA) Effect has been discovered in ultrathin ferromagnetic layers, showing that the external electric field can influence the magnetic anisotropy of multi-layer structure. Applying this principle in MTJ, conclusion can be made that bias voltage applied on the oxide layer of MTJ is capable to modulate the interfacial magnetic anisotropy and thus affect the energy barrier between parallel (P) and anti-parallel (AP) states of MTJ's free layer. Therefore, based on VCMA Effect, several novel MTJ devices can be demonstrated, achieving more energy-efficient and faster MTJ switching operations.

In this manual, we will introduce three approaches to MTJ switching operations associated with VCMA effect and exhibiting fast switching capability（<1ns） and ultralow dynamic power consumption(<10fJ/bit).

The basic structure of VCMA-MTJ is sandwich structure with Ferromagnetic Layer/ Oxide Layer/ Ferromagnetic Layer. In this model, we use the common structure consisting of CoFeB(1.4)/MgO(1.4)/CoFeB(1.1) (numbers are nominal thicknesses in nanometers) (see Fig1(a)). This model solves magnetization state of MTJ's free layer in the time domain differential form according to part of experimental parameters, classical LLG equation and corresponding magnetic resistance model of MTJ etc.

Specifically, this model contains magnetic precession model of VCMA-MTJ, STT-assisted magnetic precession model of VCMA-MTJ as well as STT-assisted and thermally-activated magnetic precession model of VCMA-MTJ.

It is used to simulate MTJ switching behaviors under given stimulation when taking the Electric Field Effect other than Spin Transfer Torque Effect into consideration, providing an easy way to start the simulation of circuit design with VCMA-MTJ/CMOS. Furthermore, the last part of this model includes the effect of thermal disturbance field, and therefore is capable to simulate the stochastic switching phenomena with temperature influence.

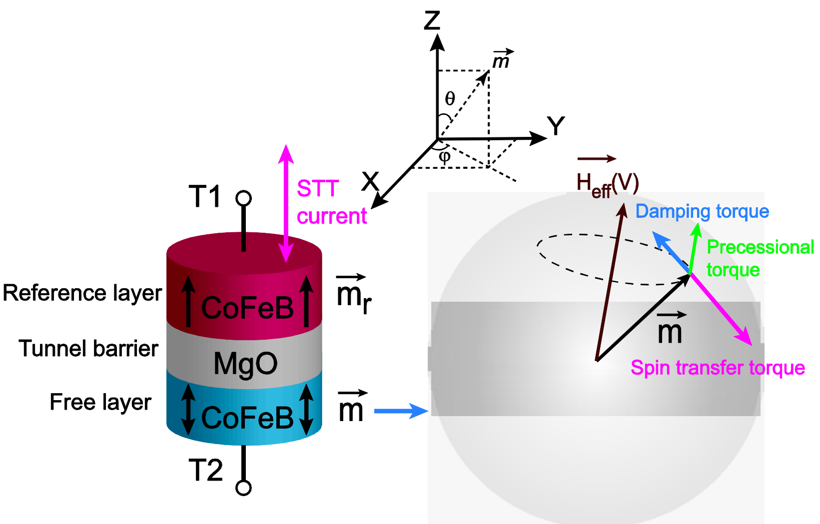

Fig.1. (a) Structure of MTJ with perpendicular magnetization anisotropy and composed of CoFeB/MgO/CoFeB thin films (b) $\vec{m}_r$ and $\vec{m}$ is the unit vector of reference layer's magnetization and free layer's magnetization respectively. In this model, the direction of $\vec{m}_r$ is fixed upward, while $\vec{m}$ moves constantly under various magnetization effect. Applying certain voltage as well as selecting suitable

pulse width can make $\vec{m}$ move from vertically up state to down state(Parallel state to Anti-parallel state) or from vertically down state to up state(Parallel state to Anti-parallel state).

The model is programmed in two versions, Matlab and Verilog-A. The Verilog-A version can be validated by Cadence 6.1.5 Spectre, 40 nm CMOS Design Kit.
More details can be find in our papers (please find them in the reference section)

II. Files Provided and Simulation Results

II.A Matlab model

Decompress the compressed file VCMA_MTJ_Matlab.rar which you have downloaded (Attention: Never rename the model out of Cadence, or a hierarchical problem would occur.), and a folder named "50nm_50nm" will appear, which contains 6 files:

Circle_Demagnetization_caculation.m
Ellipse_Demagnetization_caculation.m
Precessional_VCMA_switching.m
STT_assisted_precessional_VCMA_switching.m
STT_assisted_thermally_activated_VCMA_switching.m
Field_assisted_VCMA_switching.m

The formula of demagnetization factor of elliptical MTJ and circular MTJ differ. Input width W, length L and thickness of free layer t_f according to demand, and the demagnetization factor N_x, N_y, N_z will be worked out through elliptic integral calculation to apply other models. The width and length default of this model are both 50nm. The remaining 4 .m files are the specific models. The default value of MTJ resistance of STT_assisted_thermally_activated_VCMA_switching model is relatively low ($20\mathrm{k}\Omega$). The primary distinction among these 4 models is their stimulation. The default values of different stimulations are as following:

1) In terms of Precessional_VCMA_switching model, firstly apply constant voltage of 1.2V (from 2ns) and we can get the dynamic variation characteristic of the z component of free layer's magnetization vector.

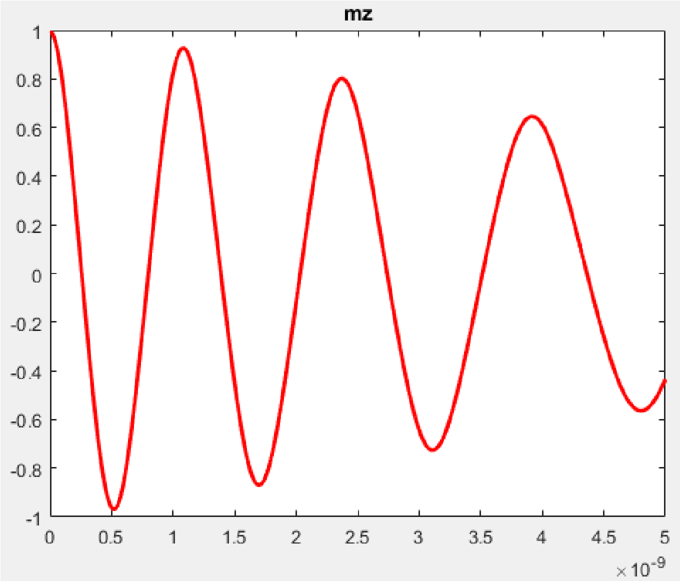

Fig 2.1 The simulation result of Precessional_VCMA_switching model under constant voltage of 1.2V(x axis – time ; y axis – magnetization state)

As for the stimulation of voltage pulse with amplitude 1.2V and width 0.5ns (from 2ns), the simulation result shows as following:

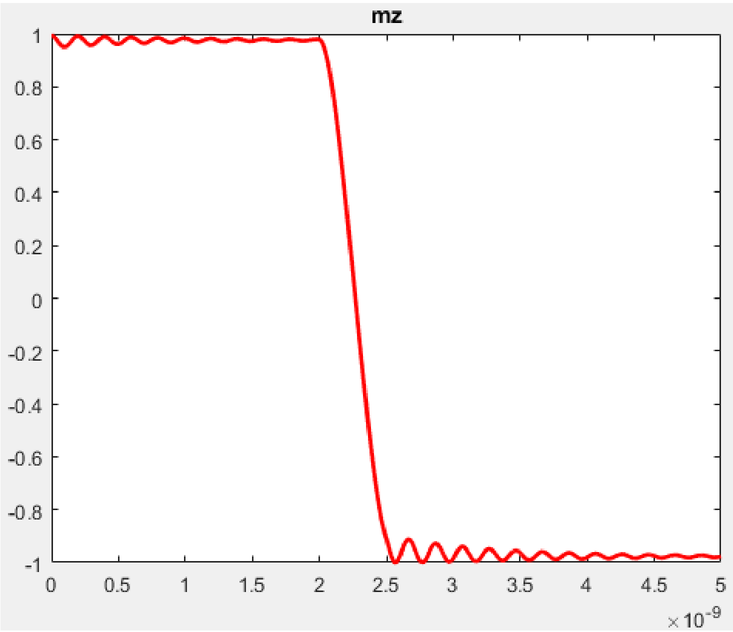

Fig 2.2 The simulation result of Precessional_VCMA_switching model under voltage pulse with amplitude 1.2V and width 0.5ns (x axis – time ; y axis – magnetization state)

2) In terms of STT_assisted_precessional_VCMA_switching, its switching stimulation is a stepped voltage pulse with amplitude 1.2V for width 0.2ns and 0.8V for 0.4ns (from 2ns). The second voltage is to produce STT current. The simulation result shows as following:

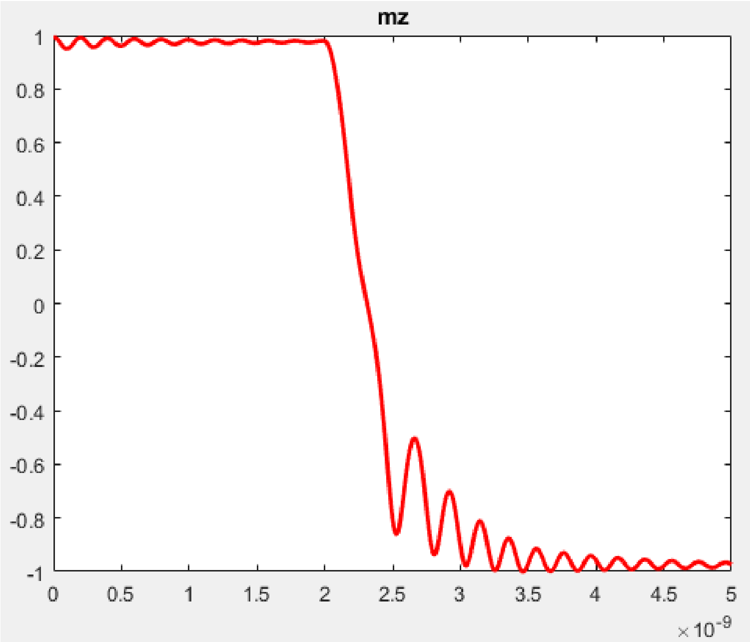

Fig 2.3 The simulation result of STT_assisted_precessional_VCMA_switching model (x axis – time ; y axis – magnetization state)

3) In terms of STT_assisted_thermally_activated_VCMA_switching, its switching stimulation is voltage pulse of $0.5\ \mathrm{V}$ and current pulse of $+1.1\ \mathrm{MA/cm^2}$ （$21.6\mu\mathrm{A}$） (starting from 2ns simultaneously), whose width are at least 14ns.

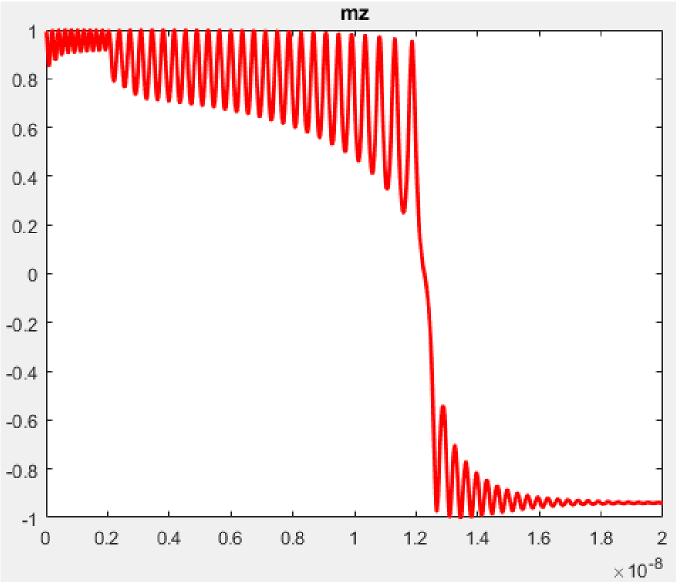

Fig 2.4 STT_assisted_thermally_activated_VCMA_switching (x axis – time ; y axis – magnetization state)

4) In terms of Field_assisted_VCMA_switching model, its switching stimulation is voltage pulse of 1.2V and magnetic field in z direction of $\pm 7 \times 10^4 A/m$ (from 2ns), lasting for at least 15ns. As for this model, because it

needs extra current streamline to generate magnetic field, making the cost of area and power consumption relatively high, it doesn't have practical value. The model here serves just as a possible switching demonstration, which will not be included in EDA models of the later part.

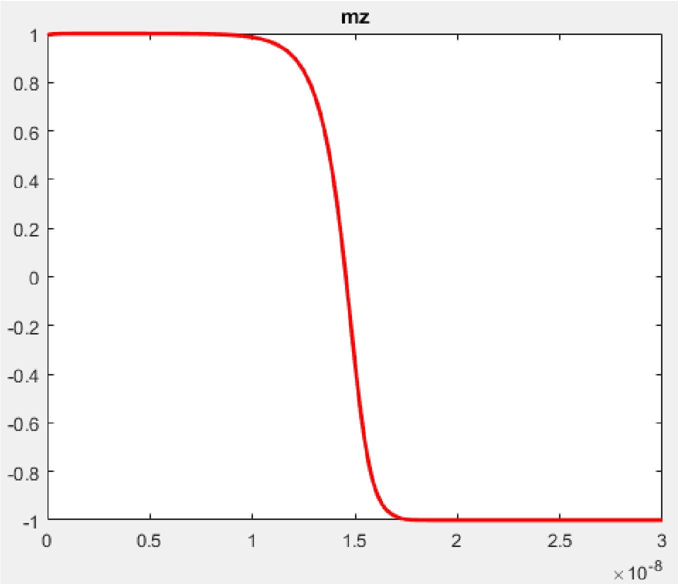

Fig 2.4 Field_assisted_VCMA_switching (x axis – time ; y axis – magnetization state)

The Matlab models above can rapidly test the accuracy of VCMA-MTJ model and whether the chosen parameters are suitable. Besides, the influence of voltage, current and pulse width on switching effect can also be explored.

II.B Verilog-A model

Decompress the compressed file ModelVCMAMTJ.rar which you have downloaded (Attention: Never rename the model out of Cadence, or a hierarchical problem would occur.), and a folder named "ModelVCMAMTJ"will appear, which contains 6 models:

Precessional_VCMA_MTJ 电压控制进动翻转模型
STT_assisted_precessional_VCMA_MTJ
STT_assisted_thermally_activated_VCMA_MTJ

II.B.a Precessional_VCMA_MTJ

Take Precessional_VCMA_MTJ model for an example, the folder contains two files: "modelVCMAMTJ" and "simuPMAMTJ".
The first file named **"modelPMAMTJ"** includes a script file of the type of veriloga, which is the source code of this model, and a symbol file (original symbol) (Fig 2.6).

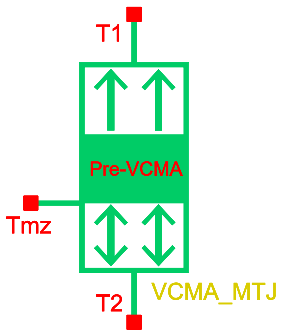

Fig.2.6 Symbol of the Precessional_VCMA_MTJ model

The symbol of VCMA-MTJ has three pins: a virtual output pin "State" is used to test the state of MTJ. Its output is the z component of free layer's magnetization vector m_z, which has influence on MTJ resistance. The more m_z approaches to 1, the more the magnetization direction of free layer and reference layer are parallel to each other, the more MTJ resistance approaches to R_P; The more m_z approaches to -1, the more the magnetization direction of free layer and reference layer are anti-parallel to each other, the more MTJ resistance approaches to R_{AP}. Due to the effect of voltage bias, MTJ resistance is related to the bias voltage when external voltage exists.Another two pins "T1, T2" are the real pins of the junction.

The second file named "**simuPMAMTJ**" is a simple test simulation case using this model in order to demonstrate how it works. The schematic of the test simulation is shown in Fig 2.7. We apply a simple voltage pulse ("V0") with suitable width(0.5ns) as input to switch the state of PMAMTJ from parallel to anti-parallel or from anti-parallel to parallel. By monitoring the voltage-level of the pin "Tmz" and the current values passing through the PMA MTJ, we can validate this compact model.(Attention: this model not only has requirement on voltage amplitude $(\mathrm{V} > \mathrm{V_c} = 1.0\mathrm{V})$,but also demands appropriate pulse width (0.2ns ~ 0.7ns).) The results of transient simulations under constant voltage (V0 = 1.2V) and voltage pulse (0.5ns,V0 = 1.2V) are presented in Fig.2.8 and Fig.2.9 respectively.

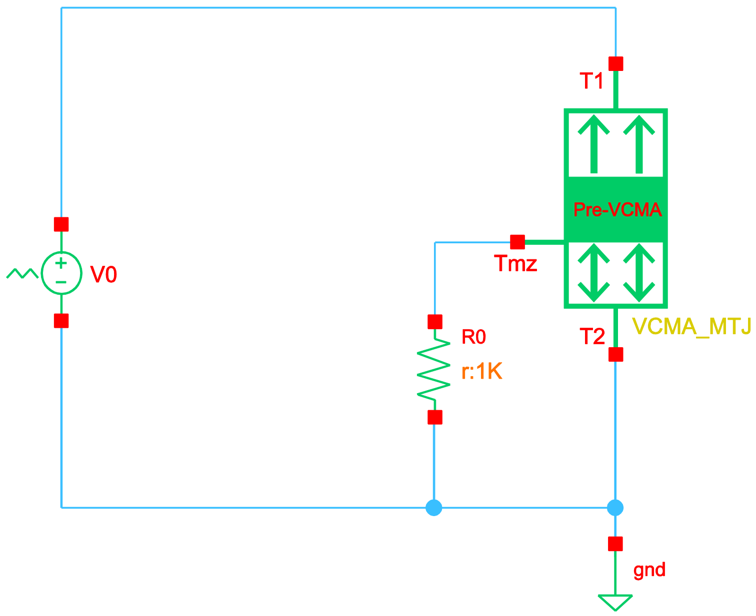

Fig.2.7 Schematic of the Precessional_VCMA_MTJ test simulation

Schematic of test simulation: VCMA_MTJ is the Precessional VCMA MTJ to be tested. Pins "T1,T2" connect to the voltage source. We can get the specific magnetization direction of MTJ's free layer by testing the output of pin"Tmz". "1" indicates parallel state, "-1" indicates anti-parallel state, others represent intermediate state.

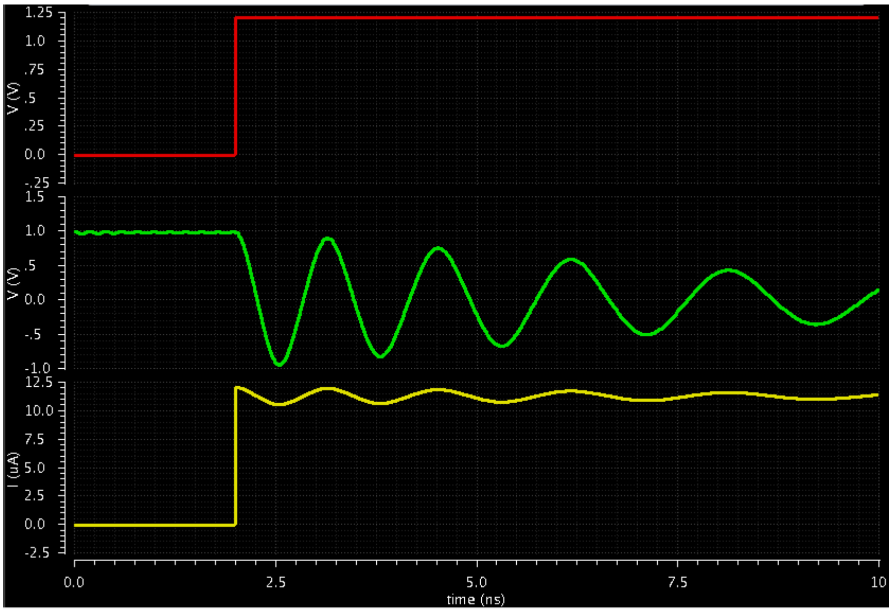

Fig 2.8 The results of transient simulations under constant voltage

Transient analysis under constant voltage: the red line represents the output voltage from voltage source, which rises to 1.2V at 2ns and then stay constant. The green line represents the z component of free layer's magnetization vector m_z, i.e. MTJ state. The yellow line represents the current through MTJ. From the figure, we can see that under constant voltage of 1.2V, the value of m_z oscillates fast between 1 and -1, which indicates that MTJ state switch reciprocally between parallel state and anti-parallel state, leading to the fast variation of MTJ resistance between R_P and R_{AP}, demonstrated by the oscillation of the yellow line representing current. The reason for the amplitude of current oscillation being not too large lies in the bias voltage effect of MTJ. TMR will decrease obviously under relatively large voltage, leading to the reduction of R_{AP}.

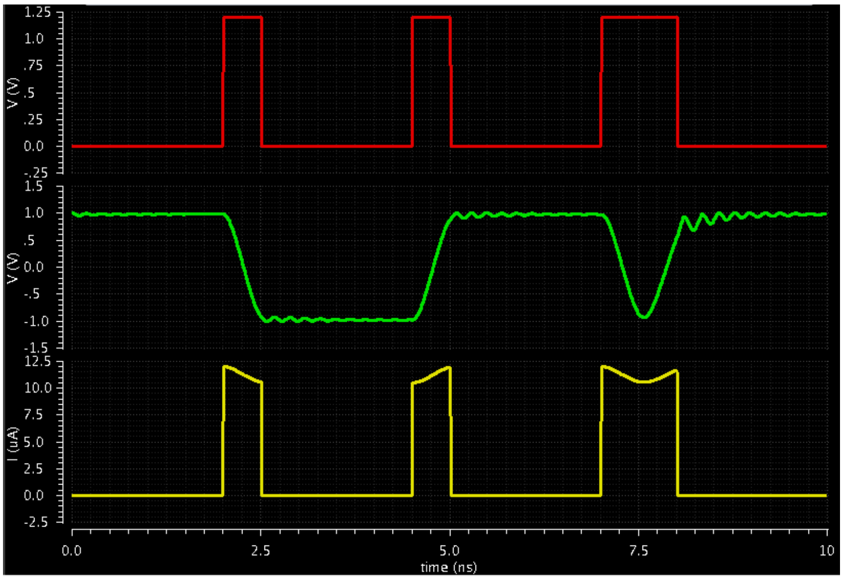

Fig 2.9 The results of transient simulations under voltage pulse

Transient analysis under voltage pulse: the red line represents the output voltage from voltage source, whose amplitude is 1.2V. The width of the first two pulse is 0.5ns and the third one is 1ns. The green line represents the z component of free layer's magnetization vector m_z, i.e. MTJ state. The yellow line represents the current through MTJ. As shown in the Fig 2.9, the 0.5ns voltage pulse can switch MTJ state from 1 to -1 (parallel to anti-parallel) or from -1 to 1(anti-parallel to parallel), while the pulse with excessive width (1ns) cannot switch MTJ.

II.B.b STT_assisted_precessional_VCMA_MTJ

The file declaration of this model accords with Precessional_VCMA_MTJ model, while Symbol has slight distinction. As shown in the Fig 2.10, "STT-Preces" in the middle manifests that this model is STT_assisted_precessional_VCMA_MTJ. Besides, this model utilize the principle of competition between VCMA and STT. Consider VCMA exclusively when $\mathrm{V} > \mathrm{V_c} = 1.0\mathrm{V}$, while consider STT exclusively when $\mathrm{V} < \mathrm{V_c} = 1.0\mathrm{V}$. The result of transient simulation shows in Fig 2.11

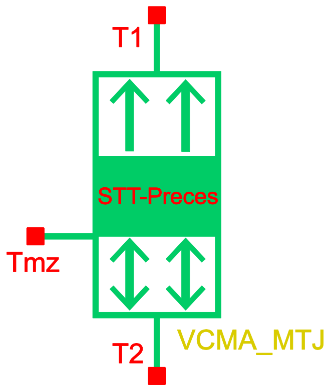

Fig 2.10 Symbol of STT_assisted_precessional_VCMA_MTJ

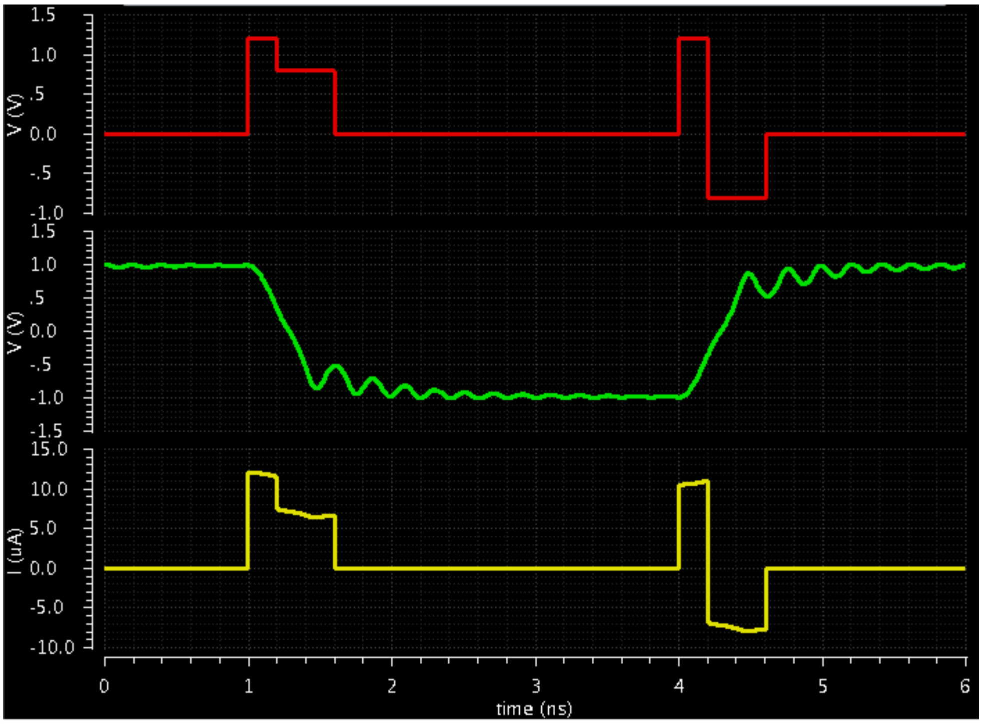

Fig 2.11 The result of transient simulation of STT_assisted_precessional_VCMA_MTJ

Transient analysis under voltage pulse: the red line represents the output voltage from voltage source, whose amplitude is 1.2V. The width of the first two pulse is 0.5ns and the third one is 1ns. The green line represents the z component of free layer's magnetization vector m_z, i.e. MTJ state. The yellow line represents the current through MTJ. The advantages of this model over Precessional_VCMA_MTJ contains that it has lower requirement on the accuracy of pulse width of the first large voltage (1.2V), higher reliability and more efficient offset against the influence of thermal disturbance.

II.B.c STT_assisted_thermally avtivated_VCMA_MTJ

The file declaration accords with two previous models, while Symbol has slight distinction. As shown in the Fig 2.12, “STT-Therm” in the middle manifests that this model is STT_assisted_thermally avtivated_VCMA_MTJ. In addition, the stimulation of this model is the simultaneous actuation of both voltage and current. Under the condition of $\mathrm{V} = 0.55\mathrm{V}, \mathrm{I} = 21.6\mathrm{uA}$, the actuation time should be at least 14ns to achieve definitive switching. The result of transient simulation shows as Fig 2.13.

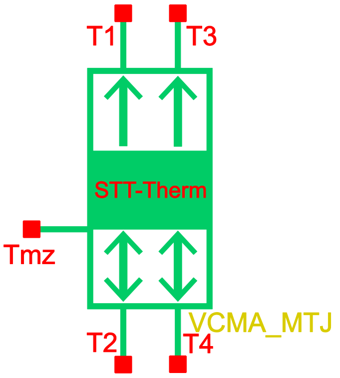

Fig 2.12. Symbol of STT_assisted_thermally_activated_VCMA_MTJ

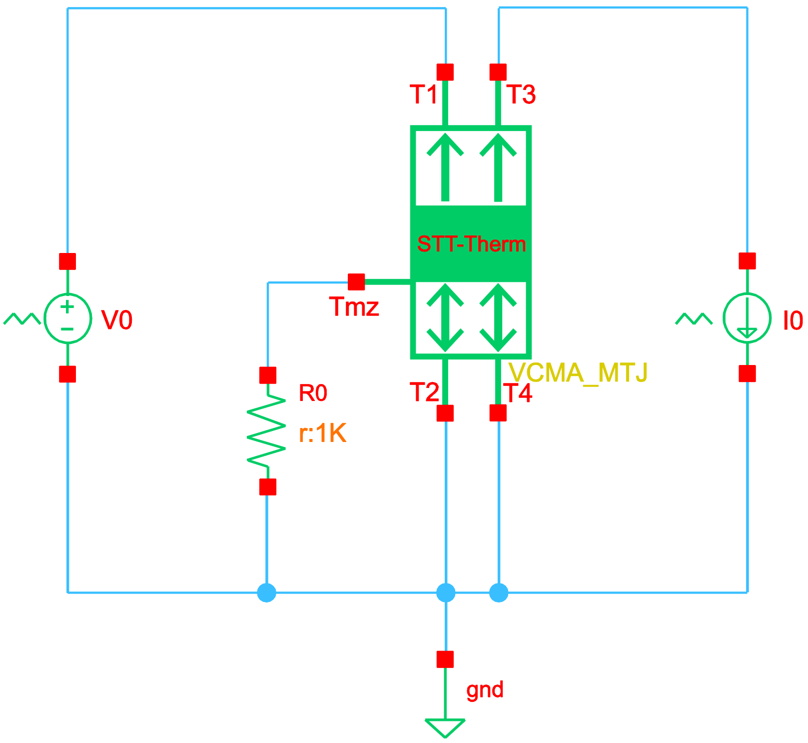

Fig 2.13. Schematic of the STT_assisted_thermally_activated_VCMA_MTJ test simulation

In terms of this STT_assisted_thermally_activated_VCMA_MTJ, current and electric field are applied in the meantime, leading to VCMA and STT respectively. Pins “T1,T2” should be applied by voltage source while pins “T3,T4” by current source. As for the switching from parallel to anti-parallel, the current flows from free layer to reference layer; when transferring from anti-parallel to parallel, the current flows from reference layer to free layer.

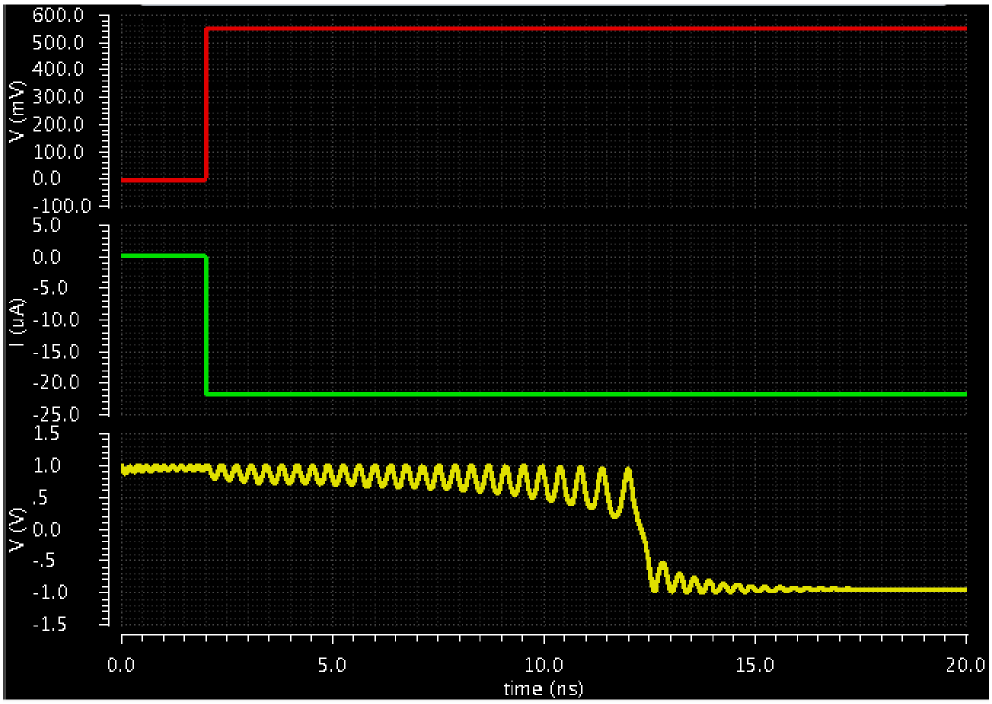

Fig 2.14 The result of transient simulation of STT_assisted_thermally_activated_VCMA_MTJ

Transient simulation analysis: the red line represents the output voltage from voltage source, whose amplitude is 0.55V. The green line represents the output current from current source, whose amplitude is 21.6uA. The yellow line represents the z component of free layer's magnetization vector m_z, i.e. MTJ state. As shown in the figure, after being actuated for a relatively long time (10ns), MTJ state completes switching from parallel state to anti-parallel state.

III. Parameters

III.A Component Description Format (CDF)

In order to describe the parameters and the attributes of the parameters of individual component and libraries of component, we use the Component Description Format (CDF). It facilitates the application independent on cellviews, and provides a Graphical User Interface (the Edit Component CDF form) for entering and editing component information.

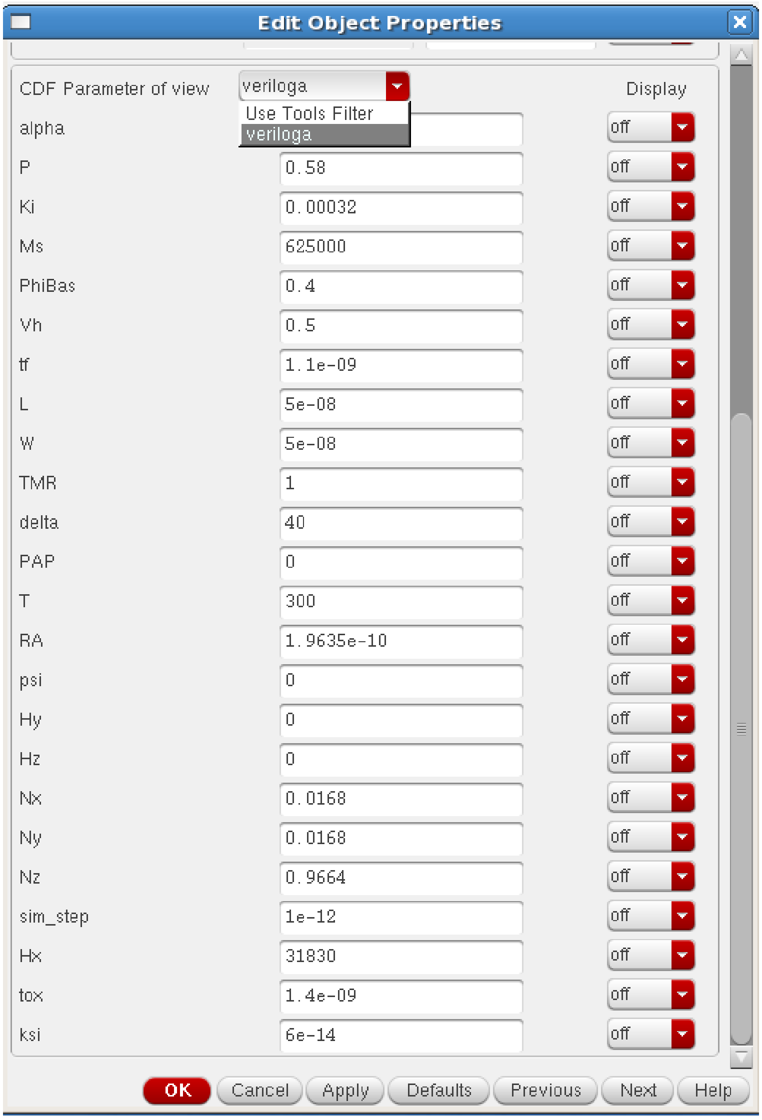

Fig 2.15 Configuration of the CDF parameters

Thanks to its favorable features, we use CDF to define the initial state of VCMA MTJ. By entering “0” or “1” in the column “PAP” in category “Property”, we can modify the initial state to parallel or antiparallel (see Fig 2.15). Furthermore, using CDF tools we can modify multi MTJs’ states individually, which facilitates implementation of more complex hybrid CMOS/MTJ circuits.

III.B Technology Parameters

Parameter	Description	Unit	Default value
Ki	Energy density of Interfacial magnetic anisotropy	mJ/m^2	0.32
Ms	Saturation Field in the Free Layer	$\mathrm{A/m}$	6.25×10^5
PhiBas	The Energy Barrier Height for MgO	eV	0.4

Vh	Voltage bias when the TMR(real) is 0.5TMR(0)	V	0.5
RA	Resistance area product	$\Omega \cdot \mu m^2$	196
alpha	Gilbert Damping Coefficient		0.05
P	Electron Polarization Percentage		0.58

These technology parameters depend mainly on the material composition of the MTJ nanopillar, the process and mask design, measured through the experiment. It is recommended to keep their default values. Among these parameters, Ki and Ms serve as important roles in this magnetic precession model. If they need modifying, please refer to Ki and Ms of the references providing concrete experiment results.

III.C Device Parameters

Parameter	Description	Unit	Default value (Range)
tox	Thickness of the Oxide Barrier	nm	1.4
tf	Thickness of the Free Layer	nm	1.1
W	Width of surface short axis	nm	50
L	Length of surface long axis	nm	50
Ksi	VCMA factor	$\mathrm{fJ}/(\mathrm{V} \cdot \mathrm{m})$	60
TMR	TMR(0) with Zero Volt Bias Voltage		100%
delta	Thermal stability factor without bias voltage		40
Hx	X component of external magnetic field	A/m	31830
Hy	Y component of external magnetic field	A/m	0
Hz	Z component of external magnetic field	A/m	0
Nx	X component of demagnetization factor		0.0168
Ny	Y component of demagnetization factor		0.0168
Nz	Z component of demagnetization factor		0.9664

These device parameters describe the device structure of MTJ, and designers can change them to adapt different requirements. The default external shape of MTJ is circle (a = b), which can be changed to ellipse according to simulation requirements. (Attention: demagnetization factor need computing through integral action once again after size factors are modified.) In terms of circular MTJ, i.e. W = L, the code for calculating demagnetization factor is Circle_Demagnetization_caculation.m; when modifying to elliptical MTJ, i.e. W $\neq$ L, according code is Ellipse_Demagnetization_caculation.m

III.D Relative Physical Constants

Parameter	Description	Unit	Default value (Range)
e	Electronic charge quantity	C	1.6×10^{-19}
m	Electronic mass	Kg	9.11×10^{-31}
μ_B	Bohr magnetron	$\mathrm{J/T}$	9.274×10^{-24}
μ_0	Permeability of vacuum	$\mathrm{H/m}$	1.2566×10^{-6}
hbas	Reductive Planck constant	$\mathrm{J \cdot s}$	1.0545×10^{-34}
kB	Boltzmann constant	$\mathrm{J/K}$	1.38×10^{-23}
gamma	Gyromagnetic ratio	$\mathrm{m/(A \cdot s)}$	2.21276×10^{5}

IV. Summary

This document introduces the instructions and simulation results of the novel MTJ's magnetic precession models based on VCMA effect, including three concrete models: Precessional_VCMA_switching model, STT_assisted_precessional_VCMA_switching model and STT_assisted_thermally_activated_VCMA_switching model . Matlab version serves for simple tests while Veriloga version provides utilization of practical EDA simulation.

V. Reference

[1] H. Zhang, W. Kang, L. Wang, K. L. Wang and W. Zhao, "Stateful Reconfigurable Logic via a Single-Voltage-Gated Spin Hall-Effect Driven Magnetic Tunnel Junction in a Spintronic Memory," in IEEE Transactions on Electron Devices, vol. 64, no. 10, pp. 4295-4301, Oct. 2017. doi: 10.1109/TED.2017.2726544

[2] W. Kang, Y. Ran, Y. Zhang, W. Lv and W. Zhao, "Modeling and Exploration of the Voltage-Controlled Magnetic Anisotropy Effect for the Next-Generation Low-Power and High-Speed MRAM Applications," in IEEE Transactions on Nanotechnology, vol. 16, no. 3, pp. 387-395, May 2017. doi: 10.1109/TNANO.2017.2660530

[3] W. Kang, Y. Ran, W. Lv, Y. Zhang, and W. Zhao, “High-Speed and Low-Power Magnetic Non-Volatile Flip-Flop Design with Voltage-Controlled Magnetic Anisotropy Effect Assistance,” IEEE Magnetics Letters, vol. 7, no. 3106205, pp. 1-4, Aug. 2016.

[4] W. Kang, L. Zhang, J. O. Klein, Y. Zhang, D. R. Ravolosona, and W. Zhao, “Reconfigurable Codesign of STT-MRAM under Process Variations in Deeply Scaled Technology,” IEEE Transactions on Electron Devices, vol. 62, no. 6, pp. 1769-1777, Mar. 2015.