Manual of Compact Model of Voltage-Gated Spin-Orbit Torque Magnetic Tunnel Junction (VGSOT-MTJ) with Perpendicular Magnetic Anisotropy

Spinlib: Model VGSOT-MTJ

Version: VGSOT-MTJ_Bate_1.1

K.L. Zhang[1,2,3], D.M. Zhang[1,2,3], C.Z. Wang[1,2,3], L. Zeng[1,3], Y. Wang[1,3] and W.S. Zhao[1,3]

[1]School of Microelectronics, Beihang University, Beijing, 100191, China

[2]School of Electronic and Information Engineering, Beihang University, Beijing, 100191, China;

[3]Hefei Innovation Research Institute, Beihang University, Hefei, 230013, China;

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Contact: deming.zhang@buaa.edu.cn and weisheng.zhao@buaa.edu.cn

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I. General Introduction

Although two-terminal perpendicular magnetic tunnel junction (p-MTJ) based on spin-transfer torque (STT) switching is the mainstream storage unit used by MRAM, it still faces some main problems, long incubation time, high switching current densities and read current disturbance.

Switching mechanism based on spin-orbit torque (SOT) effect in heavy metal/ferromagnetic metal/oxide hetero-structures by applying an in-plane charge current in three-terminal devices is a potential alternative mechanism. However, it is essential that an external field is applied to the SOT device to achieve deterministic switching in p-MTJ, which limits the application of SOT-MRAM. Luckily, current experiment results have demonstrated that p-MTJ based on the antiferromagnetic (AFM)/ferromagnetic (FM)/oxide structure can achieve field-free SOT switching, because the AFM can not only generate the SOT but also provide an exchange bias (H_{EX}) which replaces the external field. But the H_{EX} provided by these structures is too weak to accomplish a complete switching, thus resulting in low reliability and a large critical switching current.

To solve these issues, a new switching mechanism based on the Voltage-

Gated Spin-Orbit Torque (VGSOT) effect has been discovered, which means to utilize the voltage-controlled magnetic anisotropy (VCMA) to assist the SOT. Based on VCMA effect, the energy barrier of MTJ between parallel (P) and anti-parallel (AP) is reduced while the bias voltage applied to the oxide layer of the MTJ is positive. Therefore, introducing the VCMA effect in the p-MTJ based on the AFM/FM/oxide structure is to reduce the critical I_{SOT}, thus resulting in enhancing the switching reliability and reducing the switching energy dissipation. Meanwhile this VGSOT_MTJ model can achieve a complete switching.

The objective of this guide is to provide an easy way to start the simulation with the VGSOT_MTJ model.

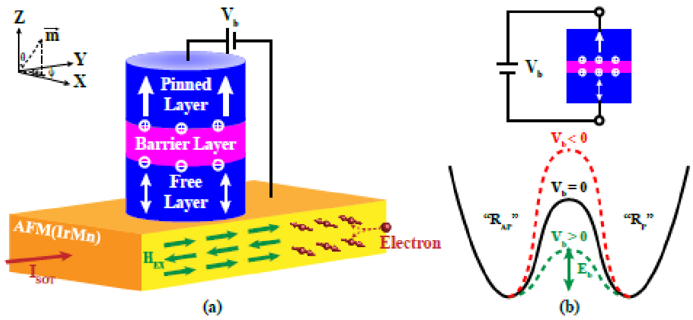

Fig1 (a) Schematic of the three-terminal VGSOT-MTJ device with the AFM/FM/Oxide structure; (b) illustration of the impact of the applied voltage (V_b) on the energy (E_b) owing to the VCMA effect.

The model is programmed in two versions, i.e., Matlab and Verilog-A. The Verilog-A version can be validated in Cadence 6.1.5 Spectre, CMOS Design Kit 28nm and 40nm.

II. Files Provided and Simulation Results

II-A Matlab model

Decompress the compressed file Matlab_model.rar which you have downloaded and a folder named "VGSOT_MTJ" will appear, which contain 8 files:

Initial.m
ELE.m
Sw.m
stochastic.m
FIELD.m
RES.m
Main_1.m
Main_2.m

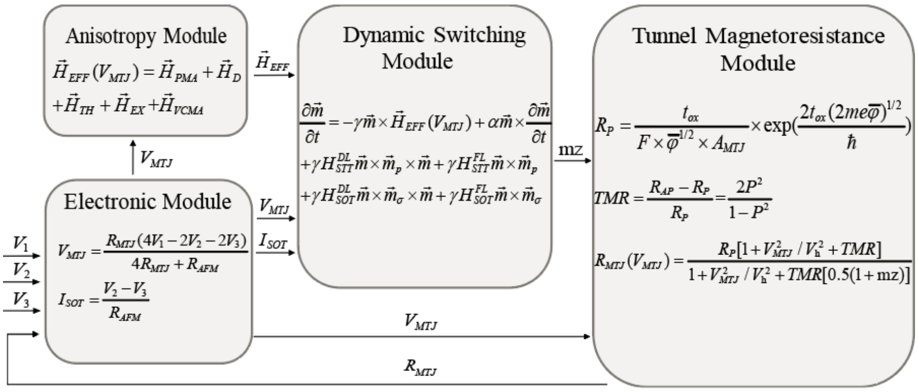

Fig.2 Block diagram of the compact model

This VGSOT_MTJ model is modularized into six parts. The first 6.m files are specific modules. The file Initial.m is the initialization module. Input initial state of MTJ (P or AP) in the Initial.m, the initial R_{MTJ} (resistance of MTJ), theta, phi, mz (z component of free layer's magnetization vector) will be worked out. The file ELE.m is the electronic module. The file Sw.m is the dynamic switching module. The file stochastic.m is a module which can generate a gaussian random number. The file FIELD.m is the anisotropy module which can generate effective field. The RES.m is a tunnel magnetoresistance module. The relationships between input and output of these modules can be obtained from the block diagram (Fig.2). The remain 2.m files are using the former modules to get the dynamic variation characteristic of the z component of free layer's magnetization vector and the resistance of MTJ. The primary distinction of the two files is their input. The default values of different setups are as following:

(1) In terms of Main_1.m, firstly apply constant voltage of 1V on V1 and constant voltage of 0.1V on V3 (from 0 to 2ns). Set ESTT to be 0(STT effect does not exist).Set ESOT to be 1(SOT effect exists).Set Ratio of field-like (FL) torque to damping-like (DL) torque in SOT effect to be 0.83 .And then we can get the dynamic variation characteristic of the z component of free layer's magnetization vector and the resistance of MTJ.

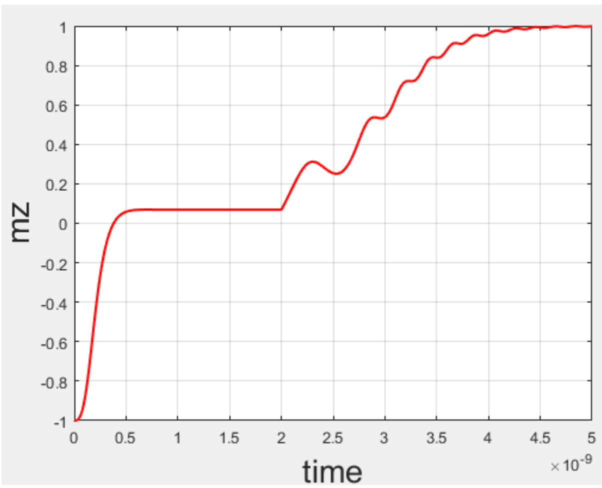

Fig 2.2 The time evolution of the mz

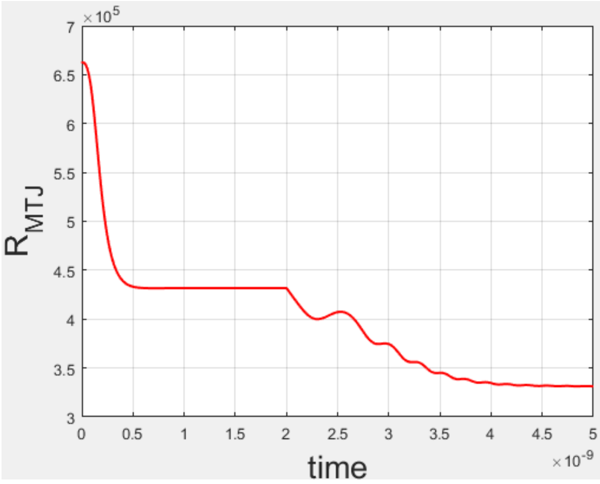

Fig 2.3 The time evolution of the resistance of MTJ

(2) In terms of Main_2.m, firstly apply constant voltage of 0 V on V_{MTJ} and constant current of -95e-6 on I_{SOT} (from 0 to 2ns). Set ESTT to be 0(STT effect does not exist).Set ESOT to be 1(SOT effect exists).Set Ratio of field -like (FL) torque to damping-like (DL) torque in SOT effect to be 0.83 .And then we can get the dynamic variation characteristic of the z component of free layer's magnetization vector.

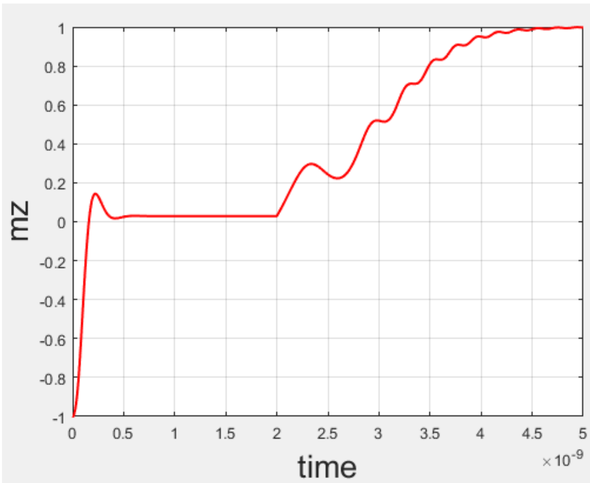

Fig 2.4 The time evolution of mz

II-B Verilog-A model

Decompress the compressed file veriloga.rar which you have downloaded (Attention: Never rename the model out of Cadence, or a hierarchical problem would occur.)

There are two files included in the decompressed file:

The first file named "VGSOT#2dMTJ#2ddevation" includes a script file of the type of Verilog-A, which is the source code of this model, and a symbol file (original symbol) (Fig. 2.6).

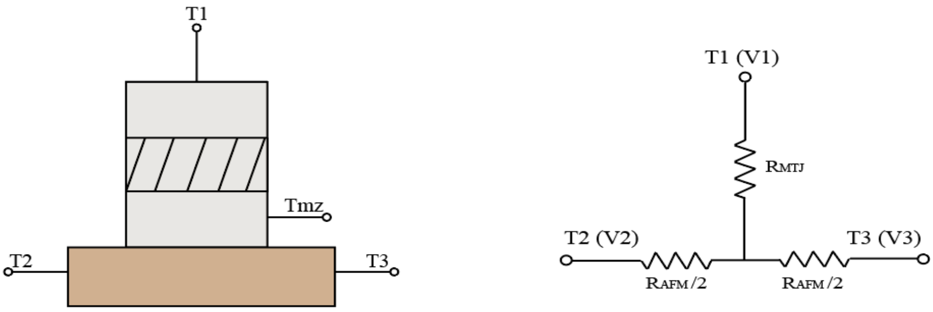

Fig. 2.6 The symbol of VGSOT_MTJ

A virtual output pin "Tmz" is used to test the state of MTJ. Its output must be one of the two discrete voltage-levels: level '0' indicates the parallel state; level '1' indicates the anti-parallel state.

Another three pins "T1, T2 and T3" are the real pins. SOT can be generated by Spin-Orbit Torque (SOT) current which is applied between T2 and T3. Conventional bias voltage can be applied between T1 and T2 (T3).

Another file named "TEST" 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.

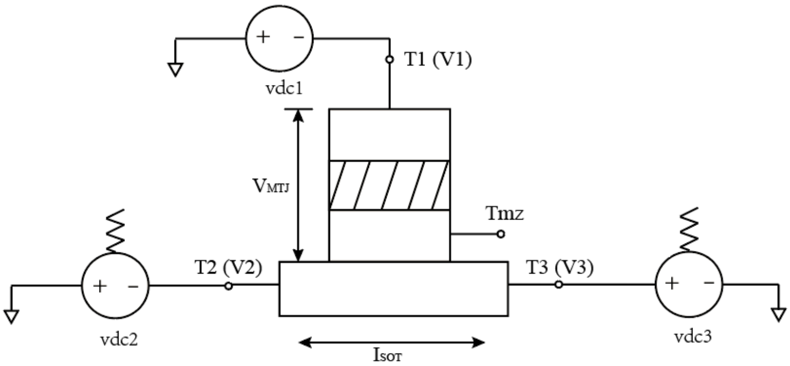

Fig.2.7 Schematic of the Test Bench

We apply three simple voltage pulses (V1, V2, V3) as input to generate I_{SOT} and bias voltage across the MTJ. I_{SOT} can generate SOT effect, and it should be a bi-direction current which can switch the state of MTJ. Bias voltage across the MTJ can reduce the energy barrier, and thus assisting to reduce the critical SOT current. T2 or T3 is usually connected to a 0 V and can also be directly grounded for better control and computing. By monitoring the voltage values of the pin "T1" , pin "T2" and pin "T3", we can validate this compact model. The results of DC and transient simulations are presented in Fig 2.8 and Fig 2.9.

The results of DC simulations show that the critical voltage of V3 can vary with the voltage of V1 while setting the voltage of V2 to a constant value (default 0). The black line indicates that the critical voltage of V3 is maximum while there is zero voltage applying on V1. While the critical voltage of V3 is minimum in the Fig 2.8, there is voltage of 1 V applying on V1(red line). With the voltage of V1 increasing, the critical voltage of V3 is decreasing. We can see the variation of resistance from the dynamic variation characteristic of the z component of free layer's magnetization vector.

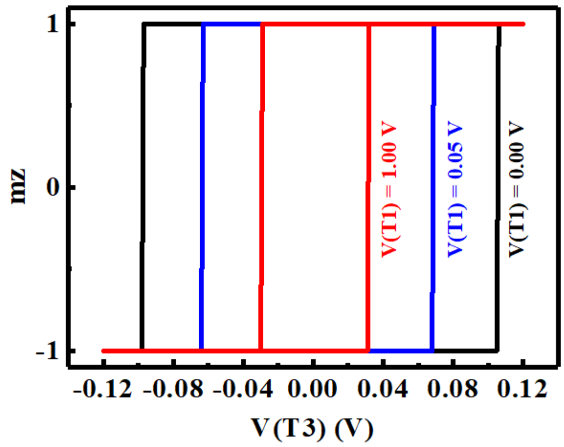

Fig 2.8 the result of DC simulations

The value of mz shows the dynamic variation characteristic of the z component of free layer's magnetization vector in Fig 2.9.

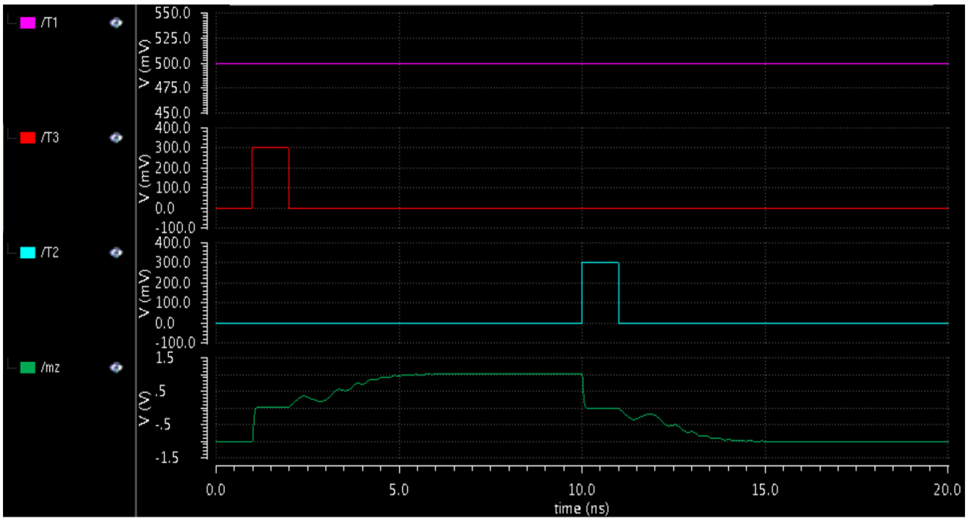

Fig.2.9 the result of transient simulations

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 cell views, and provides a Graphical User Interface (the Edit Component CDF form) for entering and editing component information.

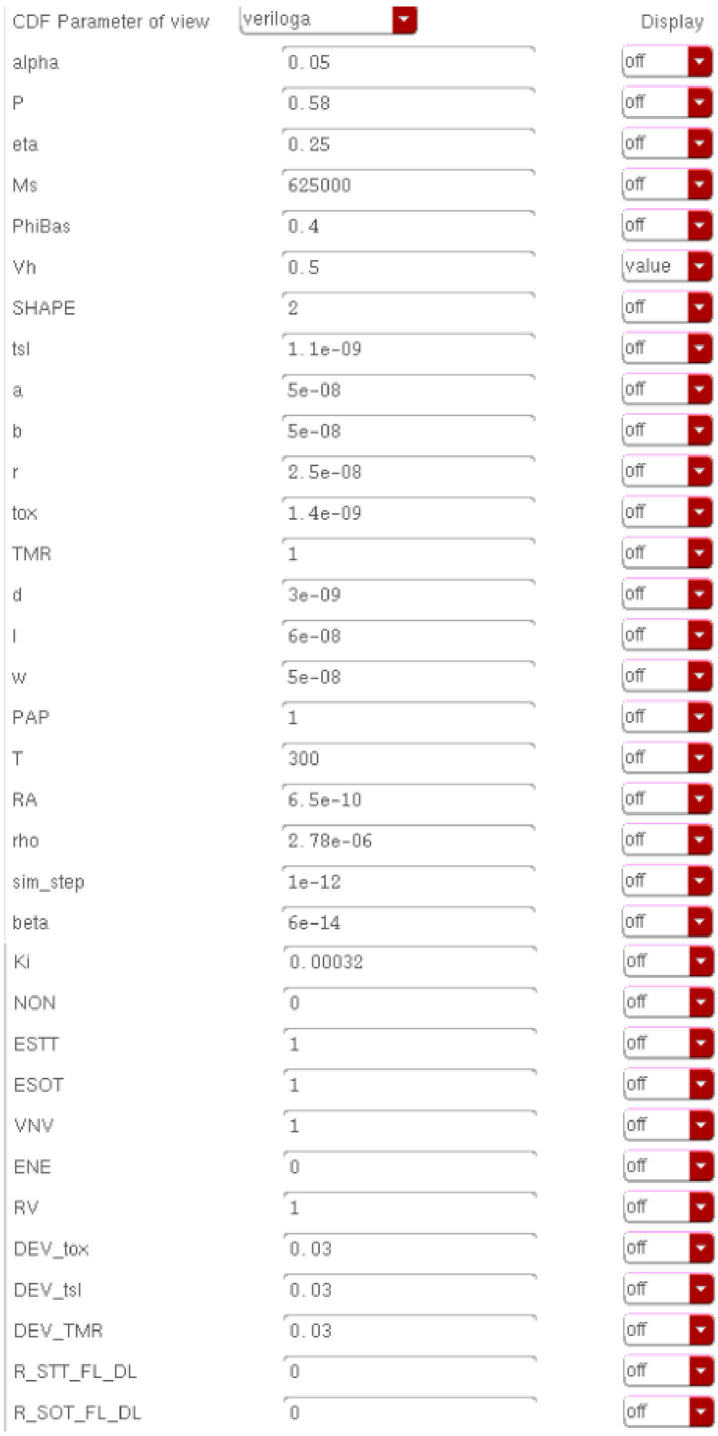

Fig.3.1 Modify the CDF parameters

Thanks to its favorable features, we use CDF to define the initial state of PMA 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.3.1). 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
alpha	Gilbert Damping Coefficient		0.05
P	Electron Polarization Percentage		0.58
eta	Spin Hall Effect		0.25
Ki	Anisotropy energy	J/m^2	0.32e-3
Ms	Saturation Field in the Free Layer	A/m	0.625e6
PhiBas	The Energy Barrier Height for Mg	eV	0.4
Vh	Voltage bias when the TMR(real) is 0.5TMR(0)	V	0.5
RA	Resistance area product	$\Omega*m^2$	650e-12

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

III-C Device Parameters

Parameter	Description	Unit	Default value
tsl	Free layer thickness	nm	1.1
tox	MgO barrier thickness	nm	1.4
TMR	TMR ratio under zero bias voltage	%	100
shape	MTJ surface shape	-	circle
a	MTJ surface length	nm	50
b	MTJ surface width	nm	50
r	MTJ surface radius	nm	25
d	AFM-strip thickness	nm	3
w	AFM-strip Width	nm	50
l	AFM-strip Length	nm	60
Hy	Exchange bias field	Oe	-50
rho	AFM-strip resistivity	$\Omega*m$	278e-8

These device parameters depend mainly on the process and mask design and the designers can change them to adapt their requirements.

The default shape of MTJ nanopillar surface is circular (using r only), but we can use also ellipse or square for specific simulation purposes.

IV. Function Option

IV-A Process variation

Beyond the Voltage-Gated SOT behaviors, the second file “TEST” adds process variation options. As the limit of the manufacturing technology, the actual thickness of oxide layer and free layer cannot be fixed at one constant value that we expected.

They always vary in a somewhat small range, but can lead to a relatively important variation for MTJ resistance. In addition, we also take the TMR ratio variation into account. The variations for these three parameters are ± 1% (see Fig.9).

Parameter	Value	Behavior
RV	0	Device parameter constant
	1	Device parameters follow a uniform distribution
	2	Device parameters follow a Gaussian distribution
DEV_tox	0.03	Variation percentage of tox when RV = 1,2
DEV_tsl	0.03	Variation percentage of tsl when RV = 1,2
DEV_TMR	0.03	Variation percentage of TMR when RV = 1,2

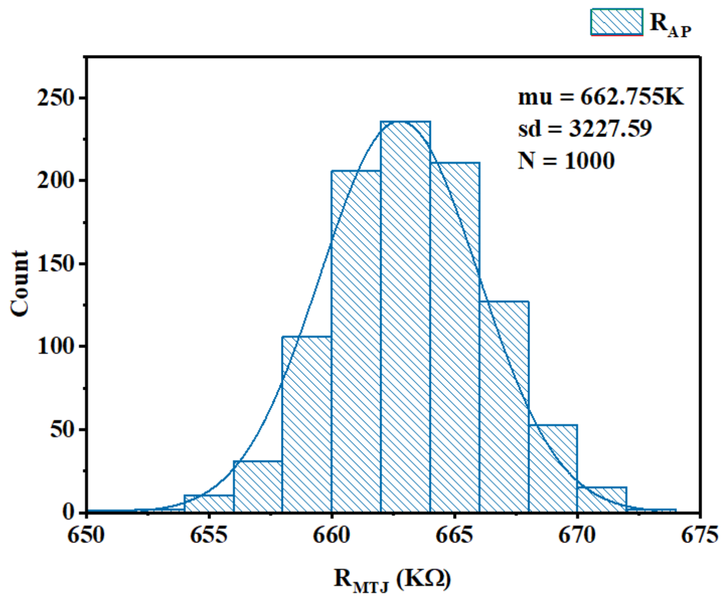

Fig.4.1 1000 times Monte Carlo results (complete stochastic switching operation simulations (parallel (P) to antiparallel (AP)))

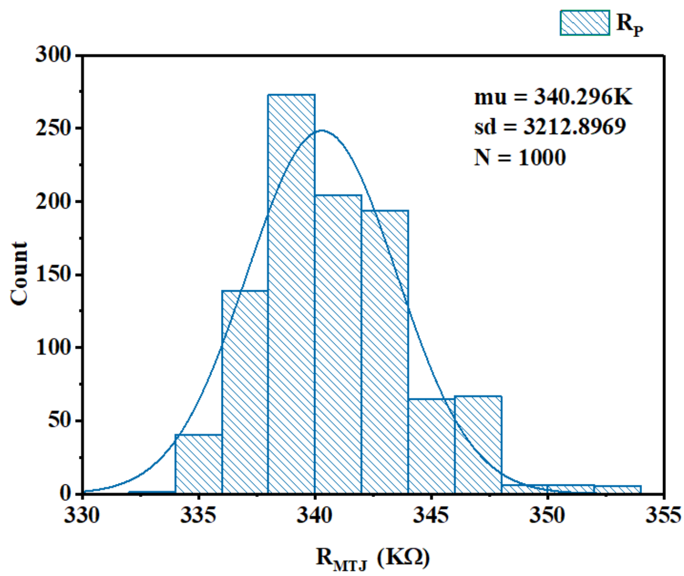

Fig.4.2 1000 times Monte Carlo results (complete stochastic switching operation simulations (antiparallel (AP) to parallel (P)))

IV-B Thermal noise

CDF parameter “NON” can be used to control whether thermal noise is considered:

Parameter	Value	Behavior
NON	0	Thermal noise does not exist
	1	Thermal noise exists

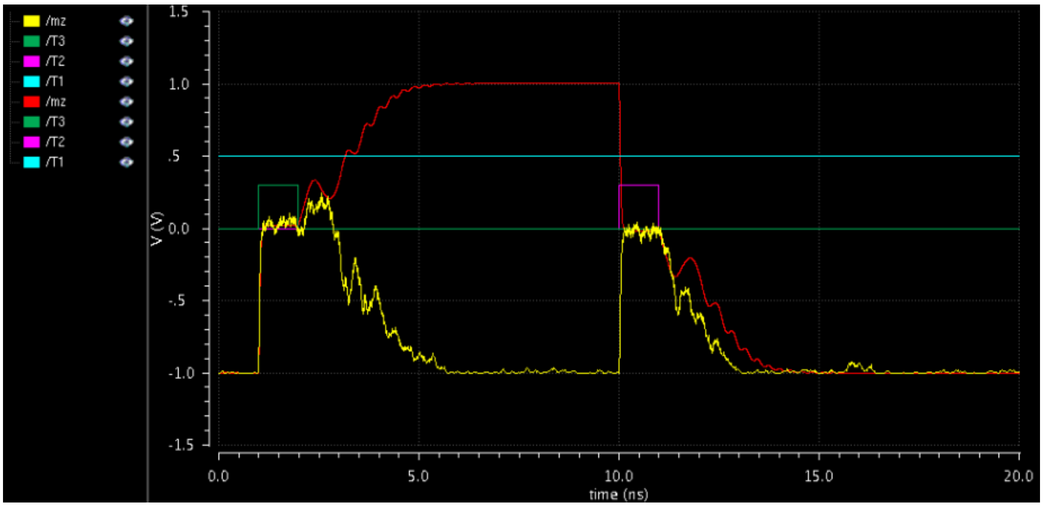

Fig.4.3 thermal noise simulation results (thermal noise exists in the simulation (red line); thermal noise does not exist in the simulation (yellow line))

IV-C Various effect combination

CDF parameter “ESTT” can be used to control whether STT effect is considered;
CDF parameter “ESOT” can be used to control whether SOT effect is considered;
CDF parameter “VNV” can be used to control whether VCMA effect is considered;
CDF parameter “ENE” can be used to control whether exchange bias field is considered;

Parameter	Value	Behavior
ESTT	0	STT effect does not exist
	1	STT effect exists
ESOT	0	SOT effect does not exist
	1	SOT effect exists
VNV	0	VCMA effect does not exist
	1	VCMA effect exists
ENE	0	Exchange bias field does not exist
	1	Exchange bias field exist

Case1: Only set the value of VNV is 0 or 1, others default value is 1

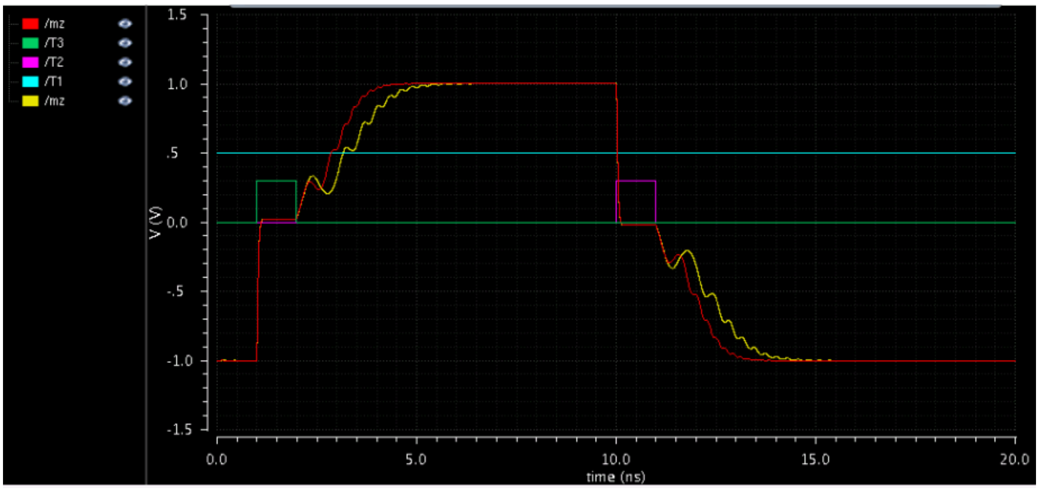

Fig 4.4 Transient simulation results (VCMA effect exists in the simulation (yellow line); VCMA effect does not exist in the simulation (red line))

Case2: Only set the value of ESTT is 0 or 1, others default value is 1

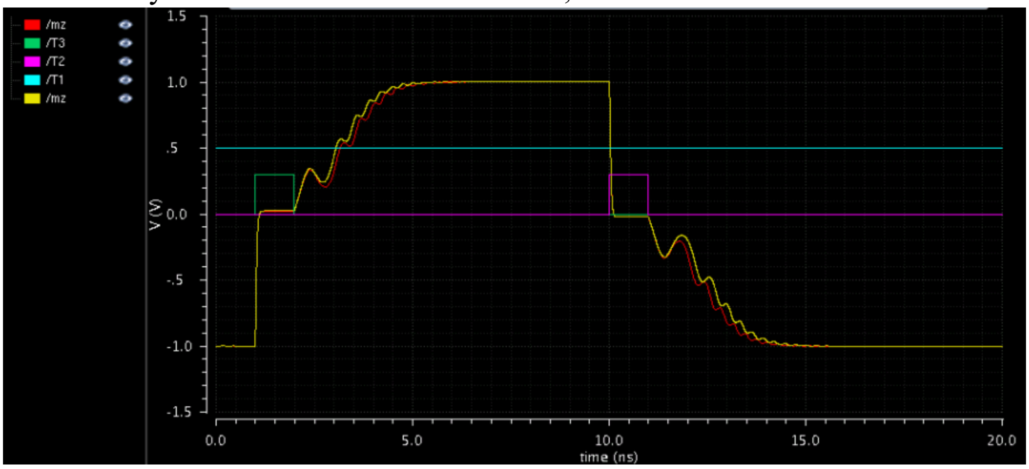

Fig 4.5 Transient simulation results (STT effect exists in the simulation (yellow line); STT effect does not exist in the simulation (red line))

Case3: Only set the value of ESOT is 0 or 1, others default value is 1

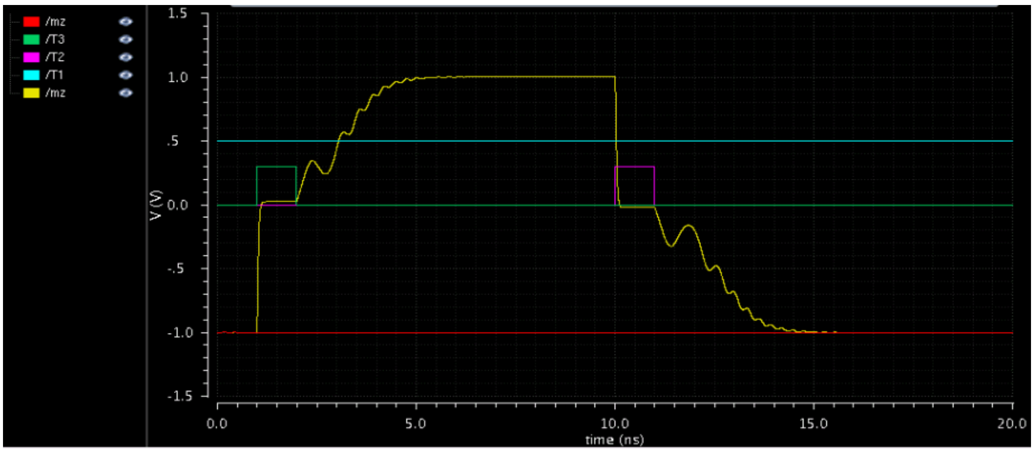

Fig 4.6 Transient simulation results (SOT effect exists in the simulation (yellow line); SOT effect does not exist in the simulation (red line))

Case4: Only set the value of ENE is 0 or 1, others default value is 1

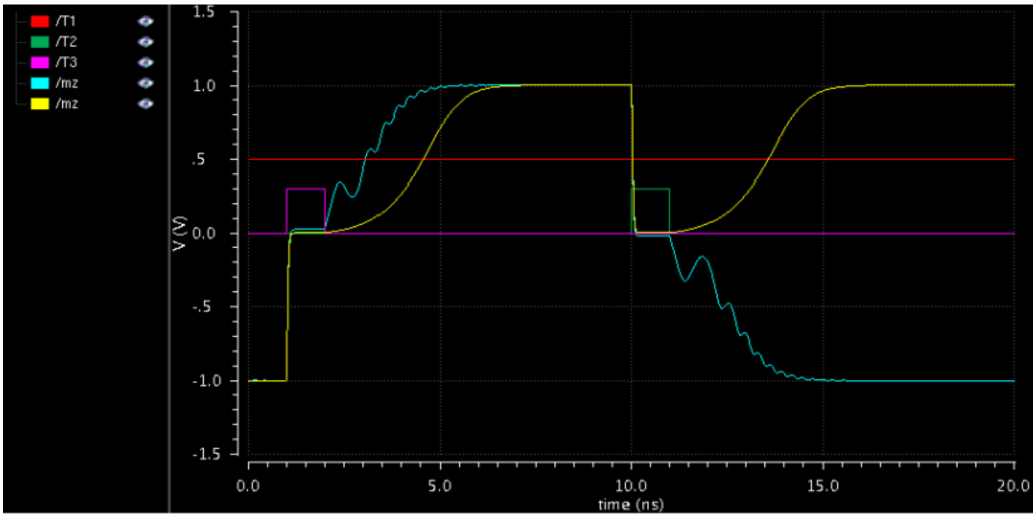

Fig 4.7 Transient simulation results (exchange bias field exists in the simulation (blue line); exchange bias field does not exist in the simulation (yellow line))

More than the above four cases, you can choose some effects existing in this model to simulate by setting the value of relevant CDF parameter to 1 according to your specific needs.

IV-D Field-like Torque

CDF parameter "R_STT_FL_DL" is the ratio between STT field-like torque and STT damping-like torque. CDF parameter "R_SOT_FL_DL" is the ratio between SOT field-like torque and SOT damping-like torque. You can modify the value of these parameters around for your particular needs.

Parameter	Value	Behavior
R_STT_FL_DL	0	Ratio between STT field-like torque and STT damping-like torque.
R_SOT_FL_DL	0	Ratio between SOT field-like torque and SOT damping-like torque.

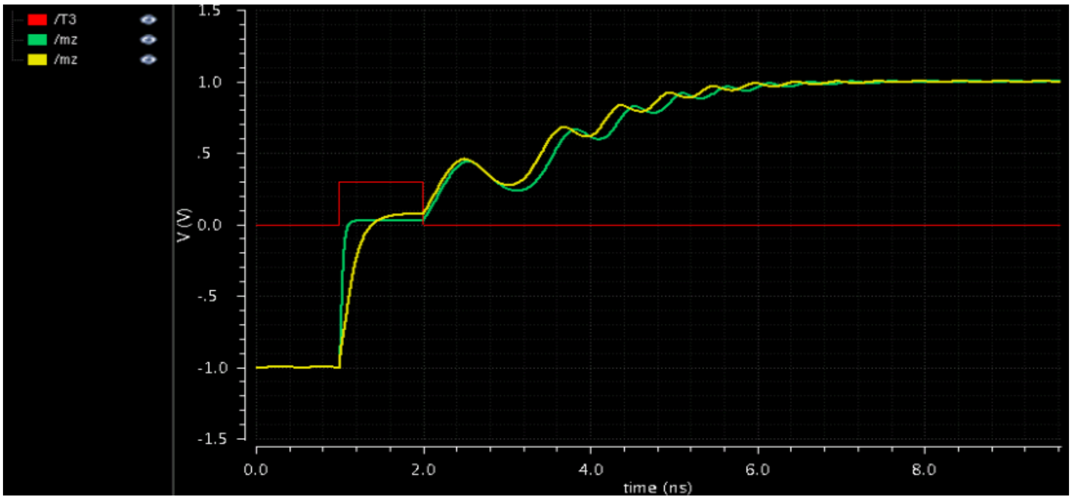

Fig 4.8 Transient simulation (set R_STT_FL_DL = 0, R_SOT_FL_DL = 0.5(green line); set R_STT_FL_DL = 0, R_SOT_FL_DL = 1(yellow line))

V. Before simulation

You need to delete an undesirable parameter “seedin” for this library, you can click Tools->CDF->Edit, Select “Base” as the CDF Type. Pick “VGSOT-MTJ-devation” as the library Name and “VGSOT-MTJ-devation” as the Cell Name that you have created. Then select the parameter “seedin” and delete it. Otherwise there will be an error occurred that “Attempt to override value of inherited parameter “seedin” when instantiating a subcircuit.”

VI. Summary

This document introduces the instructions and simulation results of the novel VGSOT-MTJ. Matlab version serves for simple tests while Verilog-A version provides utilization of practical EDA simulation.

VII. Reference

[1] Kaili Zhang, Deming Zhang, Chengzhi Wang, Lang Zeng, You Wang and Weisheng Zhao, “Compact Modeling and Analysis of Voltage-Gated Spin-Orbit Torque Magnetic Tunnel Junction”, IEEE Access, vol. 8, no. 1, pp. 2169-3536, Mar. 2020. DOI: 10.1109/access.2020.2980073