Manual of compact models for Shape Perpendicular Magnetic Anisotropy Double Layer Magnetic Tunnel Junction (s-PMA DMTJ)

SPINLIB: Model s-PMA DMTJ

Version: PM_Beta_4.0

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Table of contents

I. General Introduction

It has to be noted that the s-PMA DMTJ model can extend the MTJ design down to 10nm through the modulation of the shape anisotropy energy. The shape anisotropy energy can be calculated based on the demagnetization field energy. Meanwhile, the model is adjustable to both the diameter and thickness change. Usually, it may be difficult for MTJ to maintain a reliable thermal stability under the 10nm diameter.

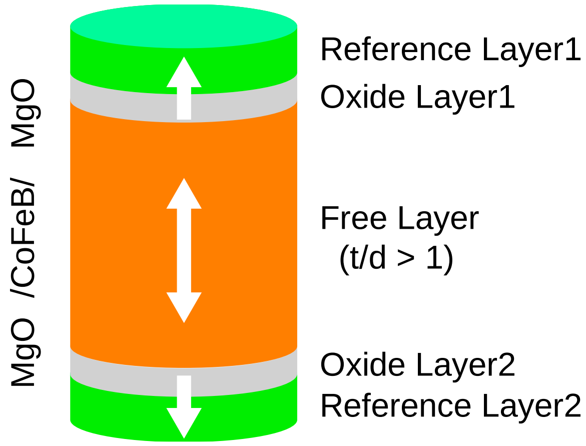

Fig. 1. The magnetic layer structure of the s-PMA DMTJ. The s-PMA DMTJ contains two reference layers which magnetized in opposite direction. The thickness of the FL is close to or even larger than the diameter.

However, recently an experiment acquired a comparatively high E_b through increasing the thickness of the junction.

The MTJ is fabricated with multilayers including

Si substrate/Ta(5)/Ru(10)/Ta(15)/Pt(5)/$[\mathrm{Co}(0.4)/\mathrm{Pt}(0.4)]_{\times 6}$/Co(0.4)/Ru(0.4)/Co(0.4)/ $[\mathrm{Pt}(0.4)/\mathrm{Co}(0.4)]_{\times 2}$/Ta(0.2)/CoFeB(1)/MgO(0.93)/FeB(15)/MgO(0.90)/Ru(5)

Programmed with Verilog-A language

Validated in Cadence 6.1.5 Specture, CMOS Design Kit 40nm.

II. Files Provided

Decompress the compressed file ModelsPMADMTJ.zip which you have downloaded (Attention: Never rename the model out of Cadence, or a hierarchical problem would occur.), and a folder named “ModelsPMADMTJ” will appear, which consists of four files.

The first file named “sPMADMTJModel” includes a script file of the type of veriloga, which is the source code of this model, and a symbol file (original symbol). The original symbol is generated from the completed veriloga file of the s-PMA DMTJ model.

The second file named “sPMADMTJCell” includes a package schematic designed with the original symbol and a symbol file of sPMADMTJ (formal symbol). The sPMADMTJ model is generated from the original symbol and peripheral circuits.

This symbol contains three pins:

A virtual output pin “State” 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

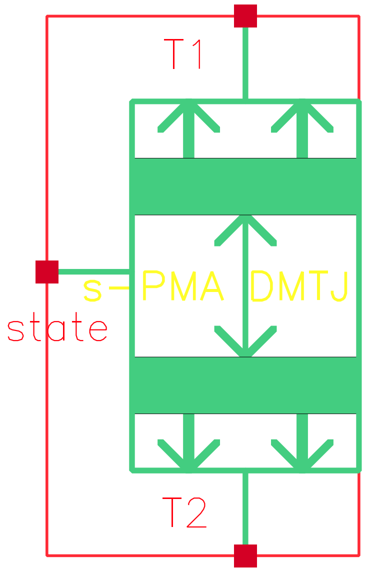

Fig. 2. The electrical model of the s-PMA DMTJ.

the anti-parallel state. Another two pins “T1, T2” are the real pins of the junction. These two pins are not symmetric: a positive current entering the pin “T1” can make the state change from parallel to anti-parallel.

The third and fourth files named “sPMADMTJDCSimu” and “sPMADMTJTransient”, respectively. The two files contain the basic simulation operation of the s-PMADMTJ model.

A test simulation case using this model in order to demonstrate how it works. The schematic of the test simulation is shown in Fig. 3 and Fog. 4. We apply a simple voltage pulse as input to generate a bi-directional current which can switch the state of PMAMTJ from parallel to anti-parallel or from anti-parallel to parallel. By monitoring the voltage-level of the pin “State” and the current values passing through the PMA MTJ, we can validate this compact model. The results of DC and transient simulations are presented in Fig. 6 and Fig. 7.

The schematics of the DC and transient simulation circuits are composed of mainly three parts. The first is the DC current source or the voltage pulse generator to provide the test signal in the circuit. The second is the s-PMA DMTJ model. The third is a resistance connected to the “state” pin of the model to act as a monitor.

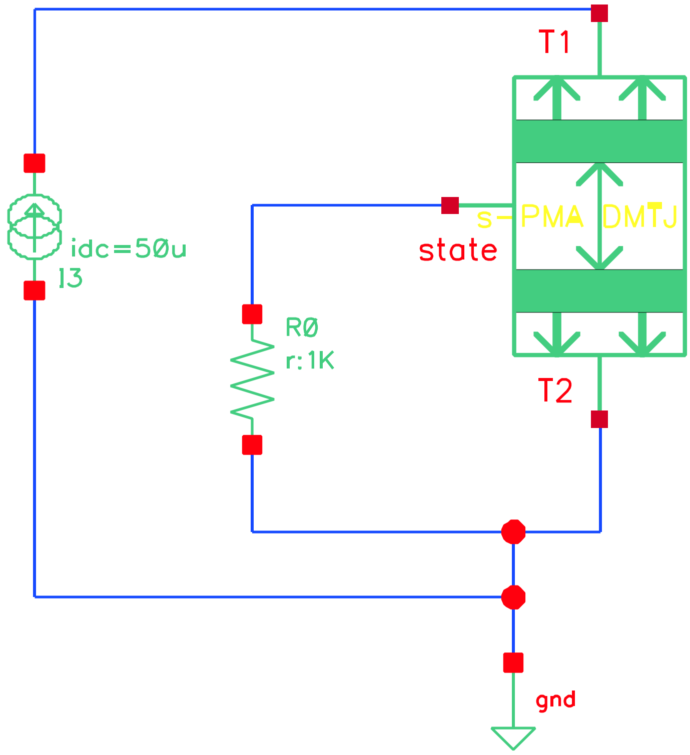

Fig. 3. The schematic of the DC simulation. The DC current source provides a scanning current range to sweep the model. The simulation results are provided in Section. III.

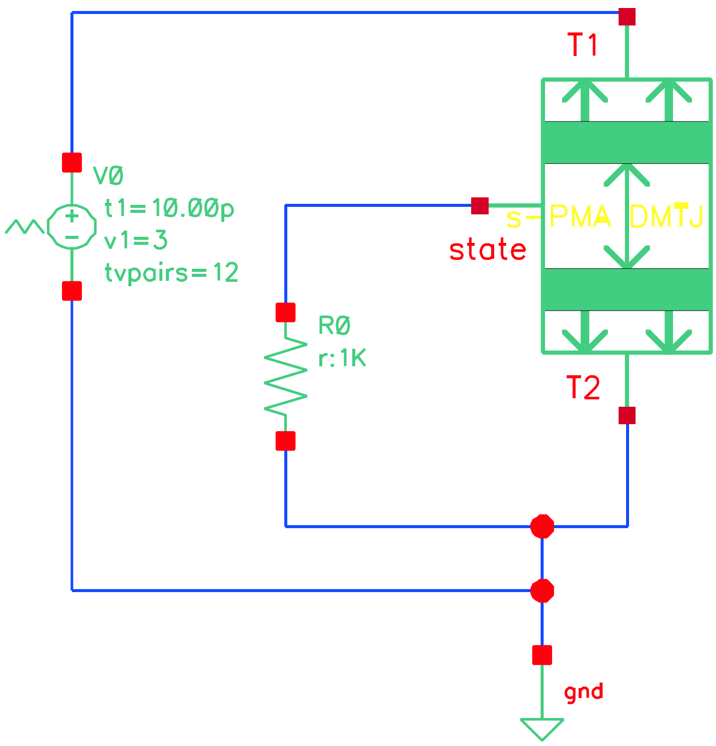

Fig. 4. The schematic of the transient simulation. The voltage pulse generator provides different amplitudes of pulses to test the transient response of the s-PMA DMTJ model. The dynamic process is also depicted in Section. III.

III. Simulations Results

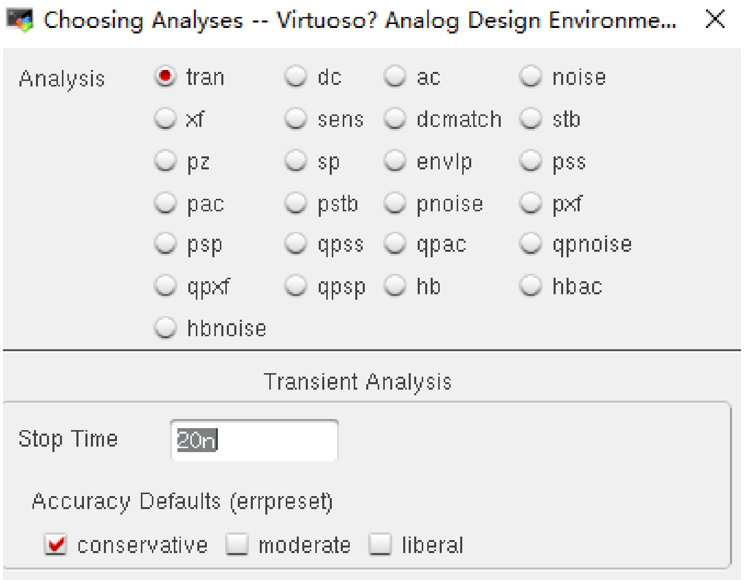

Fig. 5. The set of Analysis choice of the DC and transient simulation.

The simulation type can be selected from the “Analysis” part of the ADE XL panel. “tran” and “dc” represent transient and DC simulations, respectively. The “Stop Time 20n” means the simulation process will last 20 nanoseconds.

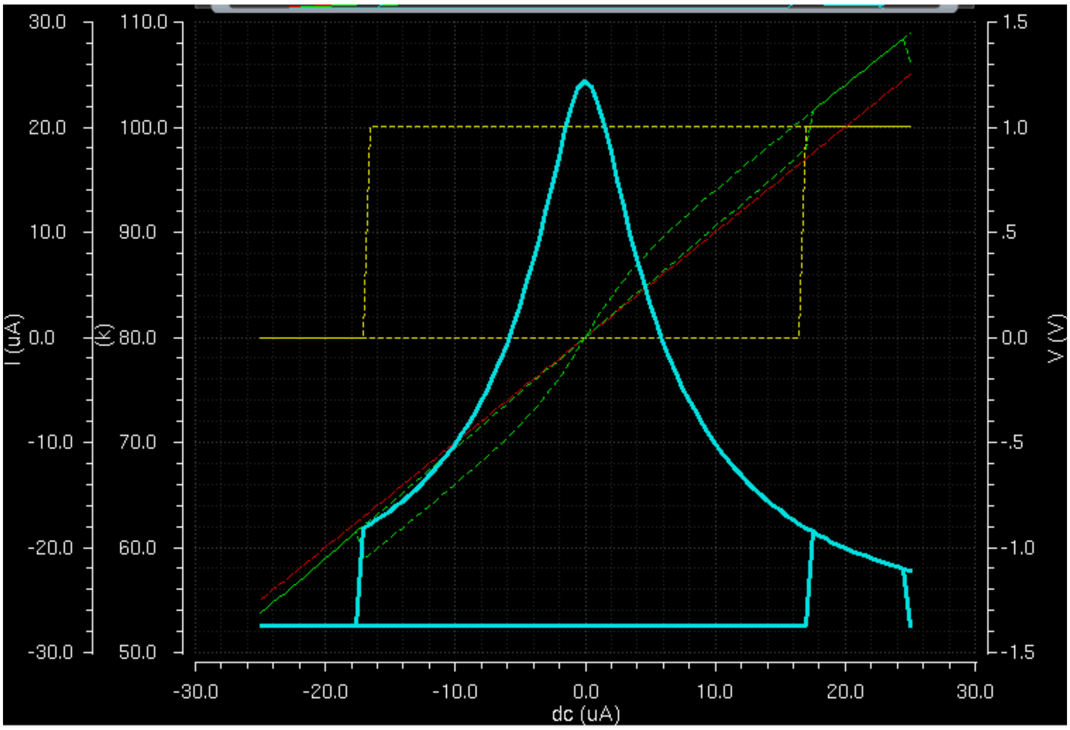

Fig. 6. The waveforms of the DC simulation results.

III. A. The DC Simulation

From Fig. 6 we can acquire the DC simulation results. The red line represents the sweeping currents from -25μA to 25μA. The green line shows the voltage value of the MTJ. While the yellow line indicates the state of the MTJ obtained through pin “state”. Additionally, we can acquire the blue line of the MTJ resistance using “Calculator” option from the panel.

III. B. The Transient Simulation

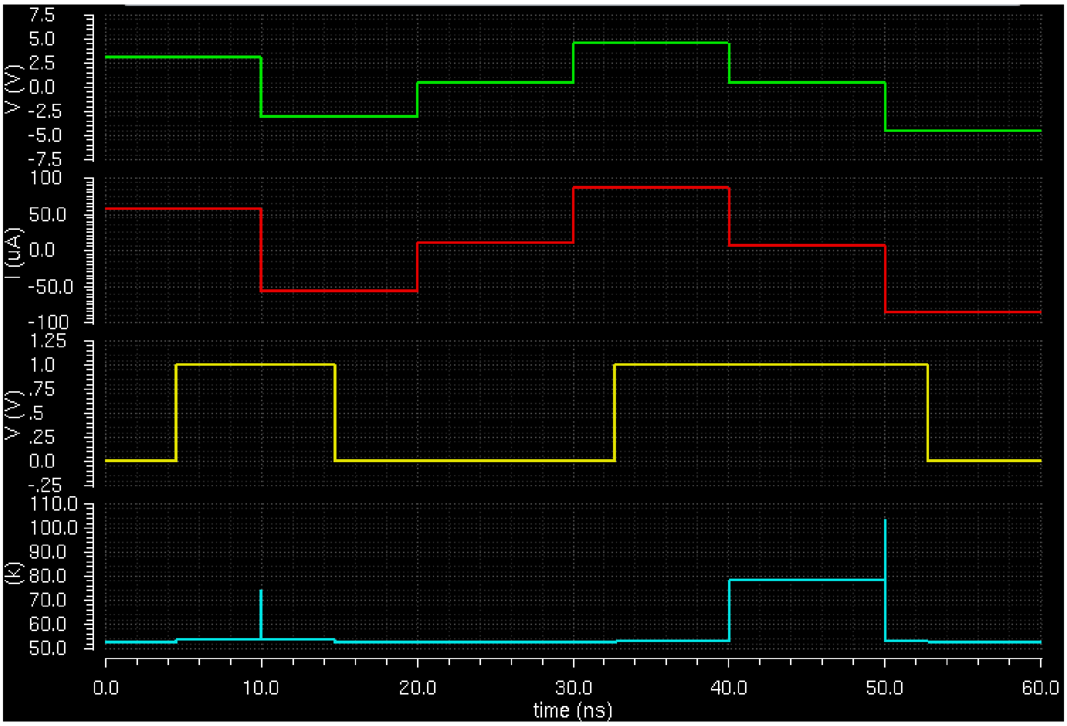

Fig. 7. The waveforms of the Transient simulation results.

The green line represents the changing voltage pulses. According to different input signals, the state of the MTJ changes to different stable states as shown in yellow line, consequently shifts to different resistances. The red and blue lines represent the current flow through the MTJ and MTJ resistance, respectively.

IV. Device Parameters

IV. A. CDF

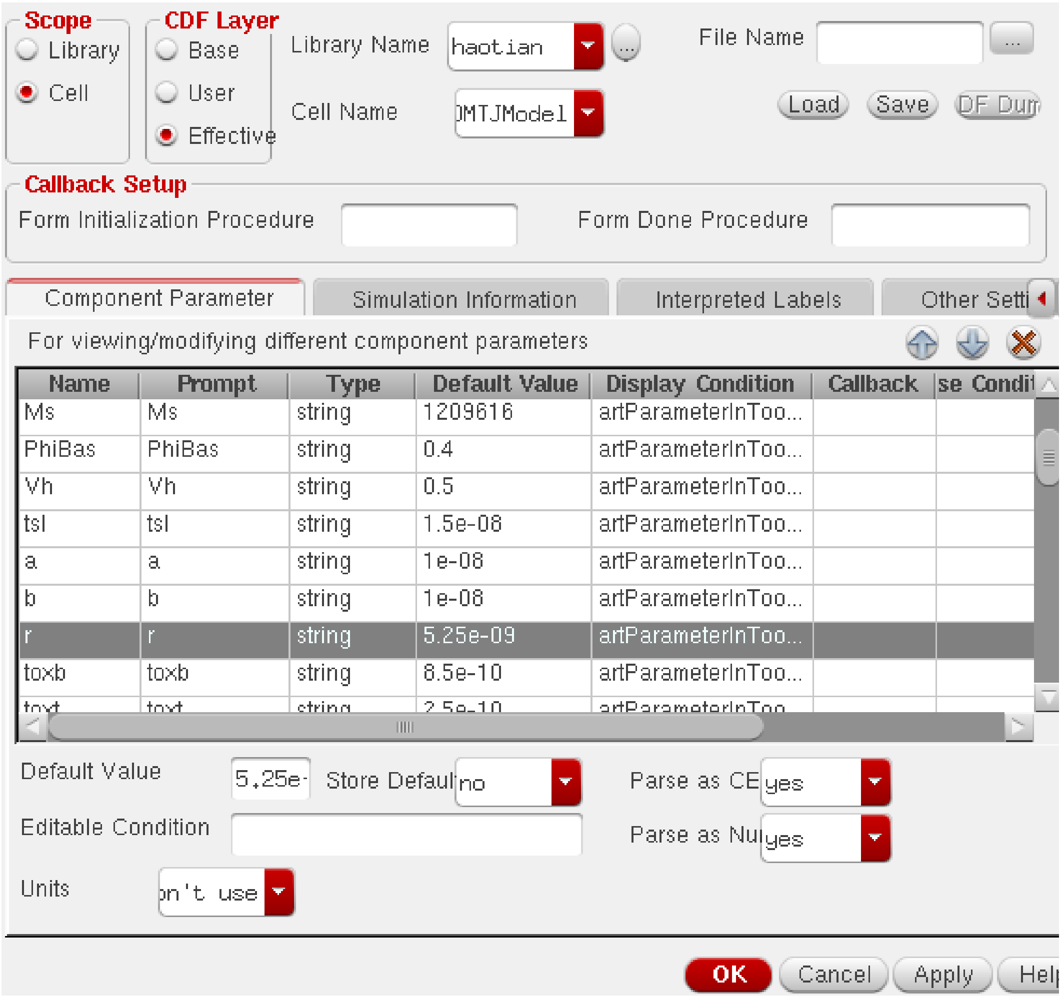

Fig. 8. The parameters acquired from the CDF panel.

In order to describe the parameters and 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.

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. 7). Furthermore, using CDF tools we can modify multi MTJ’s states individually, which facilitates implementation of more complex hybrid CMOS/MTJ circuits.

IV. B. Shape Parameters

Parameter	Description	Unit	Default value
D	Diameter of the free layer	nm	10.5
t	Thickness of the free layer	nm	15
$t_{OX}(T)$	Top oxide layer height	nm	0.25
$t_{OX}(B)$	Bottom oxide layer height	nm	0.85
$TMR(0)$	TMR ratio with 0 bias		100%

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. The s-PMA DMTJ model has two oxide layers with different thicknesses. One oxide layer is comparatively thinner as the TMR issue. And mainly to consider is the value of the free layer thickness. Usually the t is at least the same or larger than D to acquire a sufficient shape anisotropy energy. The TMR(0) is set as 100%.

IV. C. Magnetic Parameters

Parameter	Description	Unit	Default value
K_b	Bulk anisotropy density	KJ/m^3	-110
K_i	Interfacial anisotropy density	$\mathrm{KJ/m^2}$	2.2×10^{-6}
M_s	Saturation magnetization	$\mathrm{A/m}$	1.2×10^{6}
α	Magnetic damping constant		0.005
P	Spin polarization		0.57
RA	Resistance area product	$\Omega \cdot \mu m^2$	4.5
V_h	Bias voltage at which TMR is divided by 2	V	0.5

These technology parameters depend mainly on the material composition of the MTJ nanopillar and it is recommended to keep their default value. The magnetic anisotropy energy mainly consists of interfacial and bulk anisotropy energy except for the shape anisotropy energy. Meanwhile, the spin polarization and resistance area product and other parameters have been listed in the table above.

V. Conclusion

This document introduces the instructions and simulation results of the s-PMA DMTJ model, including four files totally. DC and Transient simulation circuits and waveforms have been provided. Additionally, CDF and device parameters have also been listed in the file to serve as a supplemental information. The model files can be utilized for practical EDA simulation.

VI. References

[1] H. Wang, W. Kang, Y. Zhang and W. Zhao, "Modeling and Evaluation of Sub-10-nm Shape Perpendicular Magnetic Anisotropy Magnetic Tunnel Junctions," IEEE Transactions on Electron Devices. doi: 10.1109/TED.2018.2877938.