International Journal of Chemical and Biochemical Sciences
(ISSN 2226-9614)

Journal Home page: www.iscientific.org/Journal.html

Modeling techniques of MTJ's in spin based devices and its results comparison

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Abstract

This paper describes an initiative study about the modelling techniques of MTJ block with consideration of different no. of terminals to MTJ and its results comparison. MTJ block basically operates as 2-terminals with STT modelling technique. Magnetic tunnel junction is a basic storage element of Memory like MRAM's. In, Further many other advanced desirable modelling techniques of MTJ are came into existence with respect to Memory applications, like MRAM, DSNVM, NVSRAM etc., MTJ modelling can be extended to include different Spintronic phenomena like basic 'Spin transfer torque' (STT) – 2 terminal to further 'Voltage Controlled Magnetic anisotropy' (VCMA) – 2 terminal, 'Spin orbit Torque' (SOT) – 3 terminal w.r.t SHE and Rasbha effect, Ferro electric tunnel junction (FTJ) – 3 terminals. These above modelling techniques of MTJ are observed in this paper and finally will compare their functionality results with respect to basic STT 2-terminal modelling of MTJ.

Keywords: Magnetic tunnel junction (MTJ), Spin transfer torque (STT), Voltage controlled magnetic anisotropy (VCMA), Spin orbit torque (SOT), Ferro electric tunnel junction (FTJ), Spin Hall Effect (SHE)

Short communication

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1. Introduction

"SPINTRONICS" is blend of electronics with spin, refers to the study of role played by electron "SPIN" in solid state physics. It enhances, functionality, high-speed and reduced power consumption. The basic building block of any spin based devices is "Magnetic Tunnelling Junction (MTJ)". MTJ structures consists of two Ferro-magnetic layers are separated by nonmagnetic layer [1, 5]. Spintronics field has emerged as a key technology for next generation data storage devices. This, data storage is carried out in terms of two spin states: *'Spin-Up'* and *'Spin Down*'; and it is denoted by two binary bits *'0'* and *'1'*. MTJ is the primary building block of this field and it is one of the most promising emerging storage devices. The simplest method of generating the spin-polarized current in a metal is to pass the current through a Ferromagnetic material. The most common application of this effect is a 'Tunnel magneto resistance (TMR)' [5].

1.1. Tunnel Magneto Resistance (TMR)

Tunnel magneto resistance (TMR) is a magneto resistive effect that occurs in a magnetic tunnel junction (MTJ), which is a component consisting of two Ferro-magnets separated by a thin insulator [5]. Tunnelling between two Ferro-magnets i.e. relative resistance change or effect amplitude is defined as:

$$\mathbf{TMR} = \frac{\mathbf{R_{ap} - R_p}}{\mathbf{R_p}} = \mathbf{n} \ldots\ldots\ldots(\mathbf{1})$$

- ❖ Rap – Resistance of anti-parallel states
- ❖ Rp – Resistance of parallel states

Generalized resistance equation is observed as:

$$\mathbf{R_{ap} = (n+1)R_p\left(R_{ap} > R_p\right)} \ldots\ldots\ldots(\mathbf{2})$$

Tunnel junctions are used to write/read the information stored in MRAM, typically '0' for parallel state and '1' for anti-parallel state [7]. The TMR effect was also defined by spin polarizations of Ferromagnetic-electrodes. The spin polarization P is calculated from the spin dependent density of states at the Fermi energy:

$$\mathbf{TMR} = \frac{\mathbf{2P_1P_2}}{\mathbf{1 - P_1P_2}} \ldots\ldots\ldots(\mathbf{3})$$

The total current in split into two partial currents, one for spin-up electrons and another for spin-down electrons. These varying depending on the orientation state of the MTJ.

Case (I): For, no voltage is applied to the junction, the electrons tunnel in both directions in equal rates.

Case (II): For, Bias Voltage (V) at the junction, the electrons preferentially to positive electrodes and vice-versa. The TMR becomes infinite if both polarizations P_1 and P_2 are equal 1, i.e. if both electrodes have 100% spin polarization. This case, MTJ acts as *Switch* that switches between both low resistance and infinite resistance. The TMR can decreases with both increasing of temperature and increasing bias voltage [6].

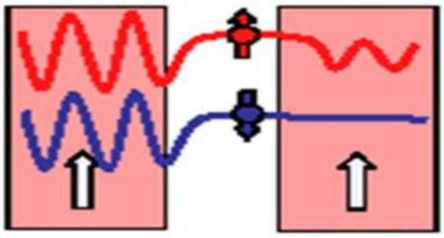


Fig 1. TMR Spin dependent tunneling

Where, Rap is the electrical resistance in anti-parallel state and Rp is the resistance in the parallel state.

1.2. Magnetic Tunnel Junction (MTJ)

Magnetic tunnel junction (MTJ) is a device whose electrical resistance is variable and depends on the magnetic state [3]. Magnetic Tunnel Junction (MTJ) device is structured as thin insulated layer is separated by both Ferromagnetic layers in which one layer is constituted with fixed spin orientation and when the spin polarized current passes through both FM fixed layer and insulating/oxide layer the spin orientation in the free FM stand either in parallel to fixed layer or anti-parallel to fixed layer; such switching happens in MTJ device.

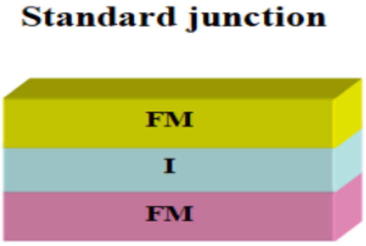


Fig 2. Basic schematic of MTJ

(i). Both FM layers constitutes same spin orientations, such it denotes both are in parallel state

(ii). Both FM layers constitutes opposite orientations, such it denotes both are in anti-parallel state.

The functionality of Magnetic Tunnel Junction (MTJ) blocks is basic with minimum of 2 terminals. It is known as 2 terminal device. But as it extends in its application scope, the inputs of MTJ increases to up to 3,4 terminals namely DSHE MTJ's. The operational is versatile in each different input modes.

2. Modelling Techniques of MTJ

Modelling of MTJ block constitutes of approach of applying different input formats in different modelling techniques and to observe MTJ parameters results in the output [3]. The basic switching operation performs only when the desired voltage is applied to block such when it passes through fixed FM layer the spin-polarized currents creates which again passes through oxide layer and it results switching in the free layer it exerting Rp or Rap resistances as in TMR [6]. There may possibly giving different input to different modelling techniques, which came to existence with versatile functioning and extend scope of application in each step of modelling. Here are some listing the different type modelling techniques of MTJ's are:

1) Spin Transfer Torque (STT) – Basic model
2) Voltage controlled Magnetic Anisotropy (VCMA)
3) Spin Orbit Torque (SOT)
4) Ferro Electric Tunnel Junction (FTJ)

2.1. Spin Transfer Torque (STT)

The basis modelling of MTJ in MRAM applications is 'STT' technique. A simple STT-MRAM is a 2 terminal MTJ in series with an access transistor, where data is stored in free FM layer orientation with respect to fixed FM layer. (i). For, Writing Information; By applying proper voltages to the both Bit Line (BL) and the Source Line (SL) with keeping an access transistor as in ON state with appropriate word line (WL) voltage such that limited amount of Charge current is passed through the fixed FM layer and in results spin polarization and vice versa for reading data from free FM layer.

(a). Schematic and Symbol STT MTJ

STT MTJ 2 terminal block consists of 1 input (T_1), 1 Grounded (T_2) and 1 Output (State). The input voltage pulse is given between two T_1 and T_2 terminals and output results will observed at output state terminal [5].

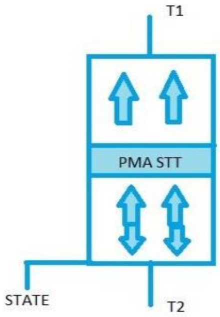


Fig 3. Symbol of STT MTJ

Further the schematic circuit of STT MTJ is designed that the both T_1 and T_2 terminals are given with ‘Vpulse’ signal and desired switching mechanism of writing & reading will observe at output state terminal [5]. The simulations is performed in Cadence tool Virtuoso Spectre with Verilog A coding of MTJ.

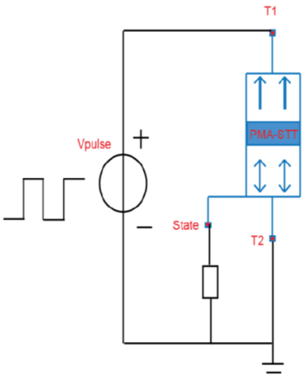


Fig 4. Schematic test circuit of STT MTJ

(b). Simulation and its summary

When input of “Vpulse” is given [-0.5v, +0.5v] range for upto time of 40ns. The polarized charge current is generated among range of [-100uA,100uA] and with this polarized the result shows how the switching happens in between either ‘0’ or ‘1’ which resembles one for ‘WRITE’ mode and other ‘READ’ mode. Here we can observe that STT MTJ exerts the delay of around ~2ns approximately in between switching.

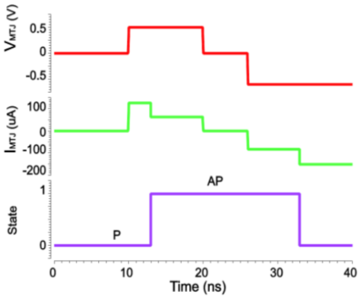


Fig 5. STT MTJ Simulation results

For ‘0v’ of input the MTJ is made stable in parallel condition and only after 10ns the input changed to 0.5v then after ~2ns delay the switching happens from Parallel state to anti-parallel state and vice versa it switching happens for every change in input with approximate of ~2.1ns delay. And most disadvantage in basic STT modeling is both ‘WRITE’ and “READ’ operations follows same path and in such case overwriting takes place. Hence this drawback can overcome in further models.

2.2. Voltage Controlled Magnetic Anisotropy (VCMA)

In the recent years enormous progress has been made in the voltage control of magnetism. This, voltage controlled magnetism anisotropy effect where the electric field across the 2 terminals T_1 & T_2, their MTJ exerts a change in the magnetic anisotropy, showing the external bias-voltage (V) an influence the magnetic anisotropy of multi layer structure [3].

(a). Schematic and Symbol VCMA MTJ

VCMA MTJ is also a 2 terminal device with T_1 & T_2 are real input pins and Tmz is output pin where the state of switching of MTJ can be observed.

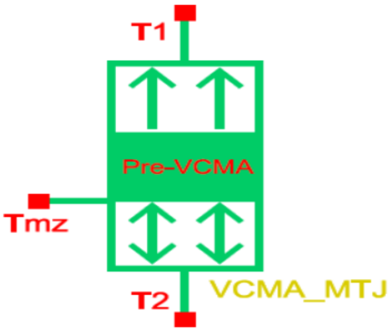


Fig 6. Symbol of VCMA MTJ

The schematic of VCMA-MTJ is shown as below; the real inputs T_1 and T_2 are given ‘Vpwl’ and output is observed at output Tmz pin [6]. The simulations is performed in Cadence tool Virtuoso Spectre with Verilog A coding of MTJ.

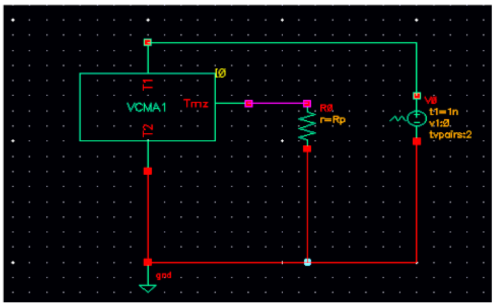


Fig 7. Test Schematic of VCMA-MTJ

(b). Simulation and its summary

In VCMA MTJ simulation, the input is given between T_1 & T_2 is given by ‘Vpwl’ with tvpairs ‘2’ and initial voltage of ‘0v’ with period of 1ns. The output is observed at output ‘Tmz’.

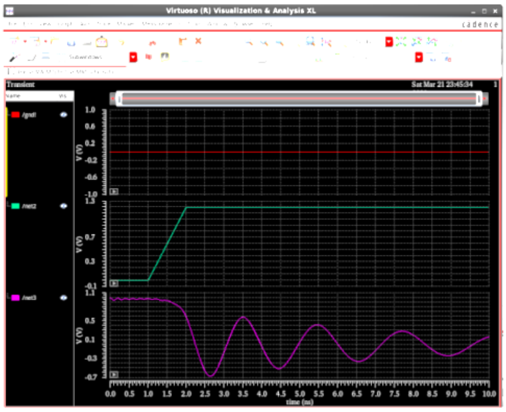


Fig 8. Simulation results of VCMA MTJ

With an ‘Vpwl’ input between T_1 & T_2 pins; as it varies in range of [0, 1] the output ‘Tmz’ observes the switching between -1 and +1. As, when ‘Tmz’ approaches to -1 it denotes that MTJ is in anti-parallel state and vice versa that when ‘Tmz’ approaches to +1, it denotes that MTJ is in parallel state and others in between state denotes as intermediate state (Delay). Here, in this model delay is observed as ~2ns. In this modeling technique of VCMA MTJ the drawback of STT MTJ of common sharing path of both ‘WRITE’ and ‘READ’ is overcoming the crosstalk by separating paths.

2.3. Spin Orbit Torque (SOT-STT)

A 3 terminal SOT MRAM is a geometrically complex device with an additional layer of Heavy Metal (HM) underneath of FL of MTJ [2]. The blue colored layer is HM layer which is an additional to the earlier MTJ modeling techniques of STT and VCMA.

(a). Schematic and Symbol STT-SOT MTJ

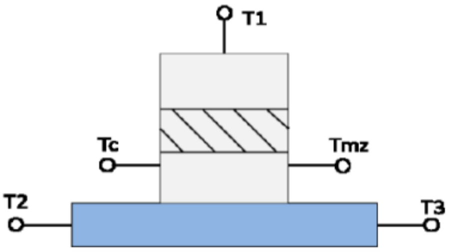


Fig 9. Symbol of STT-SOT MTJ

SOT switching in HM/FM/Oxide/FM layers are by applying in-plane charge current in 3 terminal device provides a promising switching mechanism in SOT MTJ. T_1, T_2 & T_3 are real input pins and Tmz & Tc are virtual output pins to observe the switching of MTJ [2]. In SOT MTJ modeling techniques, the interesting phenomena known as “SPIN ORBIT TORQUE” coupling can be exploited to create a Torque on storage layer of magnetization and switching it. Two fundamental physical phenomena responsible for the SOT switching mechanism are: ‘SPIN HALL EFFECT’ and ‘RASBHA EFFECT’; where the SHE effect undergoes with Jc current induced into heavy metal layer which helps in writing data into MTJ and while Rasbha effects undergoes with separation of all different orientations by spin-up to one side and other spin-down [2].

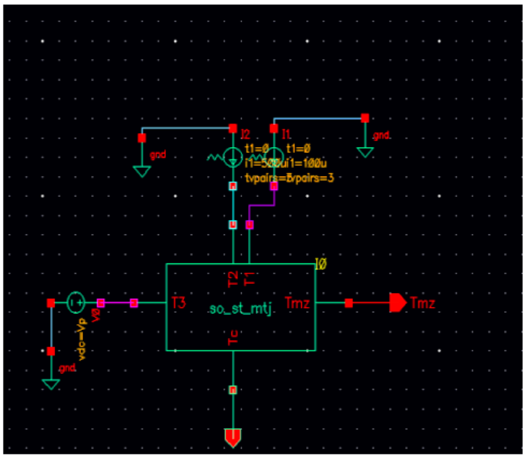


Fig 10. Test Schematic of STT-SOT MTJ

The schematic of STT-SOT MTJ is shown above; that the terminals T_1, T_2 & T_3 are real inputs-T_1 & T_2 are given with ‘Ipwl’ with 3 pairs, initial voltage to 0v & period of 1ns and T_3 is given with 1v of Vdc voltage-then the switching output is observed at Tmz & Tc. The simulations are performed in Cadence tool Virtuoso Spectre with Verilog-A coding of MTJ.

(b). Simulation and its summary

The inputs T_1 & T_2 with ‘Ipwl’ and T_3 with Vdc of 1v are given:

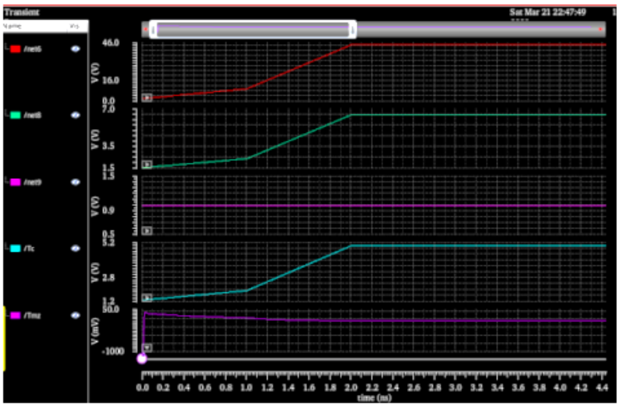


Fig 11. Simulation results of STT-SOT MTJ

T_1 and T_2 terminals are given with Ipwl with 3-pairs each and T_3 is given with Vdc=1v; the output ‘Tmz’ is noted that VT_1 and VT_2 are observed in the graph as it varying in increment way (+current–>the output Tmz switched immediately with minimum delay towards parallel to antiparallel in vice versa) and with no-inputs of VT_1, VT_2, Vdc in the graph –the output Tmz is observed as Sine-wave with negative values with respect to internally existing SHE. And the delay is observed as ~1.6ns approximately as by separating the both 'WRITE' and 'READ' paths.

2.4. Ferro Electric Tunnel Junction (FTJ-MTJ)

An FTJ consists of a ferroelectric insulator sandwiched between two different metal electrodes. FTJ model is controlled as "Voltage-controlled device". It is a 3 terminal device which operates in versatile by inclusion of both electrical and magnetic effects. The information is stored in the electric polarization of the insulator [6]. The FTJ resistance is a function of the electric polarization of the insulator.

The Charge currents of FTJ MTJ consist of three main components:

(i). Fowler Nordheim (FN) Tunneling

(ii). Direct Tunneling

(iii). Thermionic Tunneling

(a). Schematic and Symbol FTJ MTJ

The symbol FTJ MTJ is shown below; that normal MTJ and FTJ are totally different in geometry i.e., FTJ is structured as Ferroelectric layer is separated by two metal electrodes [8]. It is a 3 terminal device with T_1 & T_2 are real input pins and output state of MTJ switching is observed at spin.

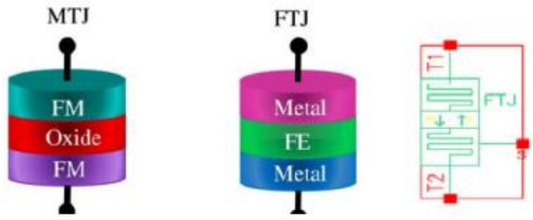


Fig 12. Symbol of FTJ MTJ

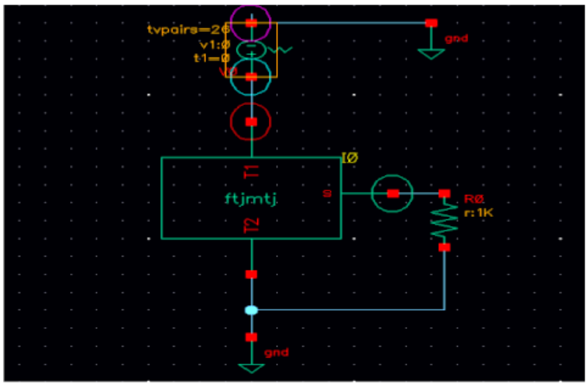


Fig 13. Test Schematic of FTJ MTJ

The schematic of FTJ MTJ is shown above; the real input pin of T_1 is assigned with 'Vpwl' with 26 pairs, initial voltage as 0v and period of 1ns. T_2 is grounded and the output is observed at output S terminal.

Fig 14. Simulation results of FTJ MTJ

It includes both TER and TMR effects and 3 mechanisms which are responsible for the TER effect resulting from the switching of Ferroelectric polarization.

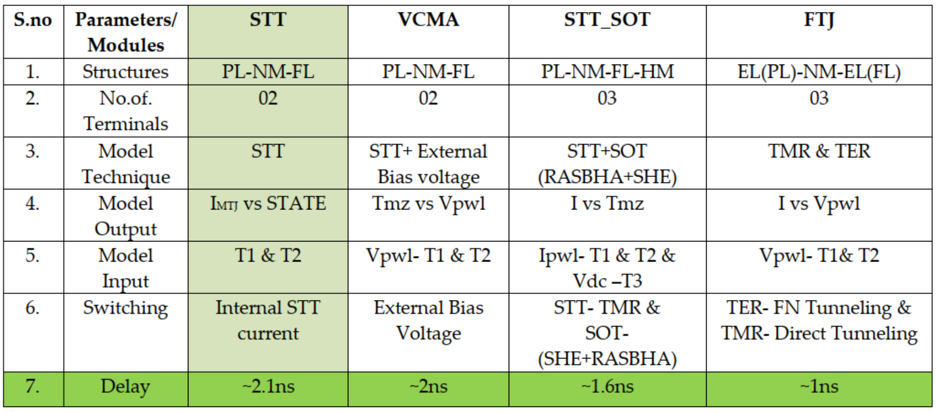
(i) Change in Electro-static profile across FE barrier

(ii) Change in Transmission Co-efficient across the interfaces

(iii) Change in attenuation constant of the Barrier

3. Results and Discussions

Table 1: MTJ Models Results Comparison



S.no	Parameters/ Modules	STT	VCMA	STT_SOT	FTJ
1.	Structures	PL-NM-FL	PL-NM-FL	PL-NM-FL-HM	EL(PL)-NM-EL(FL)
2.	No.of. Terminals	02	02	03	03
3.	Model Technique	STT	STT+ External Bias voltage	STT+SOT (RASBHA+SHE)	TMR & TER
4.	Model Output	I_{MTJ} vs STATE	Tmz vs Vpwl	I vs Tmz	I vs Vpwl
5.	Model Input	T1 & T2	Vpwl- T1 & T2	Ipwl- T1 & T2 & Vdc –T3	Vpwl- T1& T2
6.	Switching	Internal STT current	External Bias Voltage	STT- TMR & SOT- (SHE+RASBHA)	TER- FN Tunneling & TMR- Direct Tunneling
7.	Delay	~2.1ns	~2ns	~1.6ns	~1ns

Conclusion

We described all 4 different modelling techniques of Magnetic Tunnel Junction (MTJ), in which we compared several parameters from basic model STT technique to every other models of VCMA, STT-SOT & FTJ. The results best confirms that the 3 terminal device of FTJ MTJ is performing better in scope of minimum delay of around ~1ns and functionality results best switching output i.e., faster switching comparing to earlier models. High TMR is resulting in FTJ MTJ model along with additionally TER effects came into existence. The drawbacks of STT MRAM of sharing common path for both 'READ' & 'WRITE' is overcome in VCMA MTJ technique and further with 3 terminal SOT-STT MRAM shows better results with minimum delay and faster switching by both SHE+RASBHA effects. Finally, among all FTJ MTJ show better scope results with minimum delay of around ~1ns and resembles with faster switching by functionality of both TER–FN Tunnelling, TMR–Direct Tunnelling and Thermionic Tunnelling in device.

Acknowledgements

Author are very grateful to my Supervisor and Research Guide Dr. Atul Kumar Nishad, Assistant Professor in the Department of Electronics and Communications Engineering at National Institute of Technology Warangal, Telangana, India, for providing me the best guidance in relevant Spintronics area and about Virtuoso Cadence tool.

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