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Magnetic Tunnel Junction Based Applications and Logic Computation

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ABSTRACT:
The growth of technology has allowed to have reduced size and low power devices. There has been substantial research going to replace the existing CMOS technology. Magnetic Tunnel Junction (MTJ) devices is one of the emerging field which has some unique characteristics such as reconfiguration capability, high speed, low power, non-volatility and adaptability with current semiconductor devices. In this paper, MTJ is used as a basic block for different application. The characterization is carried out with MTJ LAB and simulations of logic computation is achieved using HSPICE. The results show the admirable performance of MTJ for various applications.

Keywords: Anti-parallel, Magnetism, Magnetoresistance, Parallel, Spin tunneling

I. INTRODUCTION

The growth of information technology has changed the ways of communication through effective tools such as mobile phones and Internet. There is a requirement of reliable mass storage devices to cope with huge storage of information in little space and for a longer duration [1]. The stored information has to be accessible instantaneously therefore the realization of high performance memory is necessity to sustain this revolution. Magnetic Random Access Memory (MRAM) is one such technology which can provide the solution of such problem. It uses Magnetic Tunnel Junction (MTJ) and its logic computation for the development of various systems [2]. Magnetic Tunnel Junction (MTJ) has the property of changing the resistance. It has unique characteristics such as non-volatility, high density, high speed and low power consumption. These will be very useful for memory device technology. MTJ has fundamental working principle where spin-dependent tunneling of electron occurs through an insulating barrier which is a mainly sandwiched between two ferromagnetic electrodes [3]. In order to adapt this memory device in practical applications, it is essential to have seamless integration with established silicon based CMOS technology [4]. The remedy of such issues have been addressed. It mainly includes the exploration of bottom electrode in a MTJ with spin on glass to have low temperature using Inter Level Dielectric (ILD) as well as patterning techniques for MTJ.

In recent times, there has been substantial growth in MRAM using MTJ because of its prominent characteristics of non-volatility and high density. In 1975, the magnetic tunneling effect was initially observed by M. Jullière (University of Rennes, France) during the study of Fe/GeO/Co junctions at 4.2 K [5]. Later on in 1982, the tunneling effect at room temperature was first recorded by Maekawa and Gafvert with a system of Ni/NiO/FM, where FM is Fe, Co or Ni. This work was unnoticed for a quite a long time because of low magnetoresistance (MR) ratio. However, the breakthrough happened in 1995 by using of amorphous Al_2O_3 tunneling barrier which were carried out by mainly two groups: T. Miyazaki's group from Tohoku University, Japan, and J.S. Moodera's group from Massachusetts Institute of Technology, USA [6]. The improvement of MR ratio was achieved upto 18% in Fe/Al_2O_3/Fe and around 12% in CoFe/Al_2O_3/Co both at room-temperature [7]. MTJ is a potential solution in semiconductor technology which may lead to the expansion of new storage devices. The architectures developed by MTJ are more efficient and also consumes less power [9]. For achieving these goals certain fundamental issues related to spin injection are required to be satisfied.

The main contribution of the paper is to focus on the basic requirements of a spin-based semiconductor technology. It comprises the generation, control and detection of the spin polarization in n and p-type at room temperature. The use of silicon/oxide/ferromagnet tunnel devices will address the issue of the same. The basic theory of MTJ devices is covered in Section II. The applications of MTJ is described in section III. Section IV emphasis on results and analysis of MTJ. The conclusion is derived in Section V.

II. BASIC OF MTJ DEVICES

MTJ works on the principal of magnetism therefore it is required to know about the different magnetic material characteristics and their properties [10].

A. Magnetic Characteristic

a) Diamagnetic:-It is a weak type of magnetism where orbital motion of electrons are used to create a magnetic moment m. As per the Lenz's law, the application of an external magnetic field reflects the individual magnetic moments of a diamagnetic material. It is magnetized in reverse polarity thus repelled by the field, counteracting the change in the applied field as shown in Figure 1. This consequences the opposite magnetic direction of the applied field. This kind of materials have very weak relative susceptibility in negative ($\sim -10^{-5}$), and has relative permeability much lesser than 1. In diamagnet material, individual moments of the atoms do not have any magnetization without external magnetic field, therefore the overall magnetization is null.

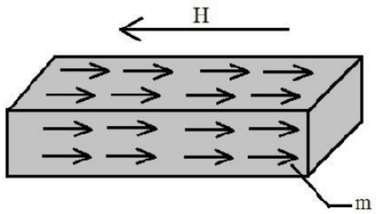


Figure 1. Diamagnetism Phenomenon [11]

b) Paramagnetic:- It also poses overall null magnetization of paramagnetic materials without any external magnetic field. However, the existence of magnetic field yields individual magnetic moment which will align to direction of the field that effects parallel magnetization in proportional to the magnetic field as shown in Figure 2. The magnetic field of these materials are still weak. Normally, the relative permeability is slightly higher than 1 and is not dependent on strength of magnetic field. It has inverse proportionality to the temperature. The relative susceptibility of this type of materials ($\sim 10^{-3} - 10^{-5}$) has inverse relation to absolute temperature.

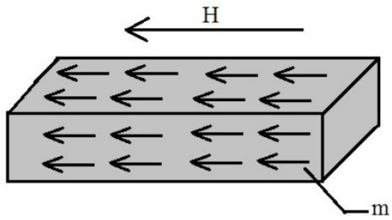


Figure 2. Paramagnetism Phenomenon [11]

c) Ferromagnetic:- It can have some magnetization without presence of an external magnetic field. Each individual magnetic moment has parallel alignment to the applied field in presence of magnetic field as shown in Figure 3. Most ferromagnets are either 3D transition metals or their alloys has 3D band which has an orbital moment (i.e., spontaneous magnetic moment) and a permanent spin. They have large susceptibility in order of 10^{6} with compare to other magnetic materials that makes easier to be magnetized. The ferromagnets have a certain magnetized limit which increase with external magnetic field.

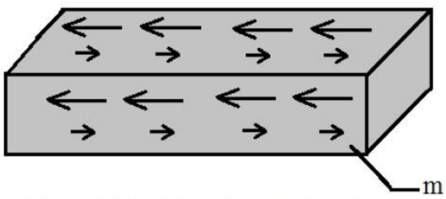


Figure 3. Ferromagnetism Phenomenon [11]

d) Antiferromagnetic:-They have magnetic moments of atoms in each lattice layer which have anti-parallel alignment because of exchange in interaction forces, however magnetization remains null in absentia of external magnetic field as shown in Figure 4. They have low permeability and low susceptibilities (some positive value), that vary with temperature similar to paramagnets. The dependence of temperature is valid for some extent of temperature which is defines as Neel temperature Θ_n. Whenever the temperature goes beyond the Neel temperature, the magnetic moments randomly oriented and subsequently the susceptibility decreases. This results in vanishing of magnetic moments and materials become paramagnetic.

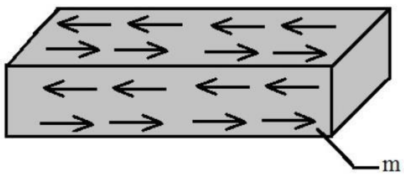


Figure 4. Antiferromagnetism phenomenon [11]

B. Magnetic Properties:

The change of resistivity in any magnetic material is measured using magnetoresistance (MR) by applying the magnetic field externally [12]. There are two types of magnetoresistance to be measured for high performance. Anisotropic Magnetoresistance (AMR) is coupled with anisotropic scattering of electrons which is caused through spin-orbit interaction. This interaction occurs between the applied magnetic field and the current density, this reflects in a change of resistance sinusoidally by applying the magnetic field**.** An AMR device has high resistance for parallel alignment of electrical and magnetic field, while it is at low resistance where electrical current is perpendicular to magnetic field.

AMR is expressed as parallel and perpendicular resistance configuration as follows equation (1):

$$AMR = 3(R_{\parallel} - R_{\perp})/(R_{\parallel} + 2R_{\perp}) \times 100\% \quad (1)$$

Here, $R_{\parallel}$ is equal to the resistance for parallel magnetic field and $R_{\perp}$ is resistance for perpendicular magnetic field.

AMR is helpful in various magnetic sensing applications such as the electromagnetic field around the conductor, Earth's magnetic field, the linear position and angular location, and so on.

In Giant Magnetoresistance **(**GMR), a thin-film multilayer structure was experienced with composition of two FM conducting layers that are mainly separated by Fe/Cr/Fe type of non-magnetic conductive material. The directions of magnetization of GMR changes the resistance by the two FM layers. The scattering effect is mainly occurred while current passing through GMR that corresponds to the FM layer which affects the spin polarizations of the current. During the parallel alignment of FM layers, the spin-polarized current can simply pass from both layers, that has lowering the resistance effect. For the anti-parallel alignment, the spin-polarized current can pass from FM layer with same polarization thereby resulting high resistance.

GMR is function of the difference between parallel and antiparallel resistance states and expressed as equation (2):

$$GMR = (R_{AP} - R_P) / R_P \ X\ 100\% \quad (2)$$

where RAP and RP are anti-parallel and parallel configurations two FM layers magnetism respectively. GMR values happen to be higher than AMR showing better performance for magnetic sensing applications.

When MTJ is in low resistance state for magnetizations of two FM layers in parallel and same way magnetizations are anti-parallel for high resistance of MTJ. The Tunnel magnetoresistance (TMR) is showed by equation (3): [13]

$$TMR = RAP - RP / RP \ X\ 100\% \quad (3)$$

III. **APPLICATION OF MAGNETIC TUNNEL JUNCTION:-**

MTJ is one of the admirable spin-based device which overcomes the limitation of traditional memory devices such as SRAM, DRAM and Flash RAM. These devices have low density, speed and endurance. MRAM can provide some key features like low operation & storage power requirements, non-volatility, unlimited endurance, low cost, high density, random accessibility and an efficient memory technology which can satisfy the computational requirements of a device [14]. MTJ is a single spin polarized current controlled device with three input terminals which can realize all logical computation as AND, OR, NAND and NOR logic functions. Some of the application area of MTJ are sensors, oscillators and RF signal generators etc.

***A. Magnetic Data Storage*:-**

The magnetic tunnel junction (MTJ) is a spin-based device and has a structure consists of two ferromagnetic layers which is separated by nonconductive tunnelling barrier (MgO, Al2O3 etc) also known as an extremely thin. MTJ demonstrates two distinct resistive states depending on the direction of magnetization because of spin-dependency. After applying a voltage across MTJ, it allows parallel orientation and tunneling of electron through thin barrier without much scattering, this resulted as a high current flow which is similar to low resistance (RP). Contrarily, to anti-parallel (AP) spin orientations produces high resistance. The change of resistance is calculated by tunnel magnetoresistance (TMR) ratio [15]. The ideal value of TMR ratio should be high in memory and logic applications. Using MgO as oxide barrier, TMR ratio can be achieved around 500% at room temperature and 1010% at 5K. In general, MTJs can have TMR ratios in between 50% and 150%.

For memory applications, MTJ uses conventional way of writing with applying two "half-select" magnetic fields that are mainly generated through current flowing in metal wires on top of the free layer. The requirement of current during writing is quite high which is also inversely proportional to device size. According to spin-transfer-torque (STT), the direct transfer of spin for magnets can control magnetization orientation through angular momentum of spin-polarized current. Thereby, MTJ current is being polarized by the fixed layer that is going to put forth a torque on the free layer which ultimately may switch the direction of magnetization if the density of current is large enough. The writing scheme of STT is illustrated in Figure 5.

The writing operation of STT has mainly switching between RP and RAP and that is controlled by the current direction. If the current flows from free layer to the fixed layer, then MTJ will be in a parallel state (RP), and vice verse for owing the current in opposite direction is resulted in an anti-parallel state (RAP). For the occurrence of switching, the writing current density should be larger than the minimum current density Jc which is necessary to switch the MTJ for a given switching time. For writing scheme of STT, MTJ is useful for a circuit design as a variable resistance controlled through bias voltage.

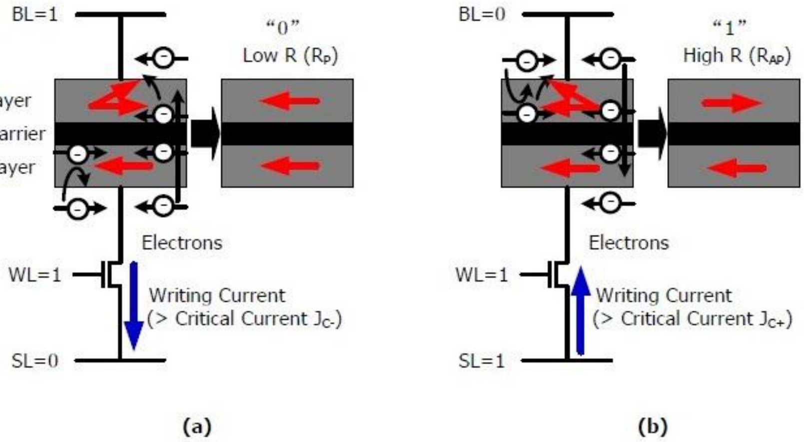


Figure. 5 Writing operation of MTJ (a) from AP to P (b) from P to AP [16]

***B. Magnetic Field Sensors*:-**

Sensors are considered to be smart electronic devices that can generate electrical signals from non-electrical physical and/or chemical quantities and also have capability to "smell", "see", "hear", "touch", and "taste". Micro sensors have a potential applications in wide market mainly as agriculture, healthcare, telecommunication etc. A magnetic field sensor converts magnetic field into the electronic signals. The magneto resistive sensors have application areas like biomolecular detection, read heads of hard disks drives, navigation systems etc. Lithography, sputtering and ion beam systems are used to serve the same purpose. The usage of magnetic materials were restricted only for magnetic moment enhancement and perpendicular anisotropy till 1988. After that, MTJ has found the most of its application in all the above mentioned domain. A sensor comprises two ferromagnetic layers that are separated by non-magnetic layer which is an insulator. To be useful as a angle sensing element, the first ferromagnetic layer is to be fixed along the direction of magnetization whereas the other is free to follow any external in-plane field direction.

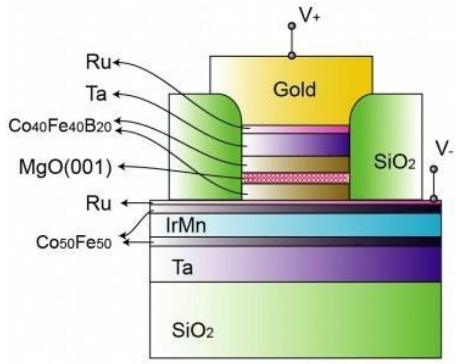


Figure 6. Layer structure of MTJ sensor using MgO [17]

***C. Magnetic Tunnel Junction in Logic Computation*:-**

A MTJ is a device which has two ferromagnetic layers, the first one is namely as the pinned (fixed) layer and the second is a free layer. These two layers are separated by a thin layer which provides an insulation and made up of metal oxide like MgO or AIO. An antiferromagnetic is a pinned layer whose magnetic orientation is always fixed. The free layer can be controlled externally and its orientation can be changed. The relative orientation of pinned and free layers decides the logic state of MTJ ('0' or '1'). If the orientation is parallel then it observed as a logic state '0' which is a low resistance. On the other end, the anti-parallel orientation specifies a logic state l that denotes as high resistance.

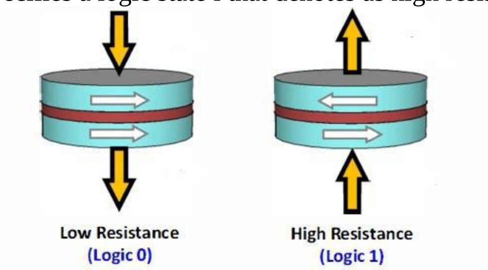


Figure 7. Two Distinct logic state in MTJ[18]

There are mainly two ways for controlling the orientation of free layer. In first method, a magnetic field is applied above a certain limit known as threshold value which is identified as Field Induced Magnetic Switching (FIMS). The different logic circuits can be implemented by this technique. However, it suffers with some scalability issues and prompts the development of another method. The second method uses Spin Transfer Torque (STT) concept where MTJ that is used to control the magnetic orientation of free layer. This technique is recognized as Current Induced Magnetic Switching (CIMS). In general, when both layers align in similar direction that creates low resistance (or logic 0 state) and in opposite direction forms high resistance (or logic 1 state).

IV. RESULT AND ANALYSIS:-

The simulation of basic MTJ characterization is obtained through MTJ LAB and HSPICE is used for simulation of logic computation. In this section, the results of MTJ characterization is discussed and also its effect on physical parameter variation which is achieved by MTJ LAB. Further, these characterization is utilized in logic calculation for HSPICE simulation.

A. RV (Resistance Voltage) characteristics of MTJ:-

When pinned layer and free layer both are in parallel orientation or in similar direction, then low resistance is occurred which is also called parallel resistance or Logic 0 state. Correspondingly, the anti-parallel orientation of both layer or in opposite direction presented a high resistance which is defined as Logic 1 state. The graph for the same is shown in Figure 8.

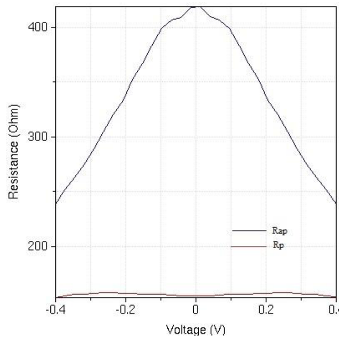


Figure 8. Parallel and antiparallel resistance

B. Tunnel Magnetoresistance (TMR) Characteristic:-

TMR is the essential measuring parameter for MTJ and the value of the same should be high [19]. The higher TMR values describes the good noise immunity and high speed of MTJ. As shown in Figure 9, the variation in voltage on TMR in the case of antiparallel resistance is maximum at zero voltage. The variation in TMR for varying voltage in parallel resistance remains almost constant for particular value of tox (here tox =1 nm). The maximum reported value of TMR is around 2.5.

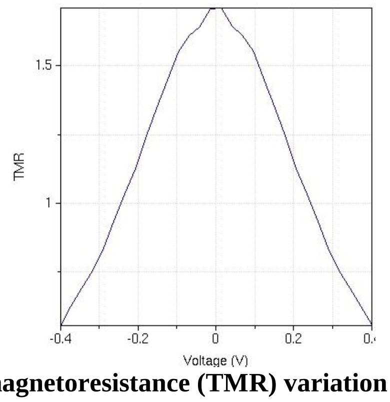


Figure 9. Tunnel magnetoresistance (TMR) variation with applied voltage

C.STT (Spin Transfer Torque) Component:-

The characteristics of STT components is shown in Figure 10. In case of CPP, the value of STT component tends to decrease with increases voltage. Initially, two ferromagnetic layers are in parallel with each other thus low resistance is experienced. But with more increment in voltage, the resistance tends to revert the state from parallel to antiparallel and reaches to high resistance which reflects in declining of current. In case of CIP, the increase value of voltage tends to increase the spin carrier electrons. This tries to alter the position therefore resistance will increase. Once it reaches to midpoint of supply voltage then it starts to decrease. In the absence of voltage, the resistance is maximum and both ferromagnetic layers are totally opposite with each other therefore maximum resistance is occurred. However, the application of voltage reflects on the tunneling of electron which align free layer to pinned layer and resistance is decreases because of applied voltage.

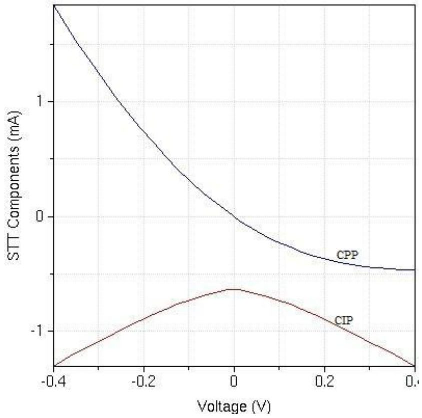
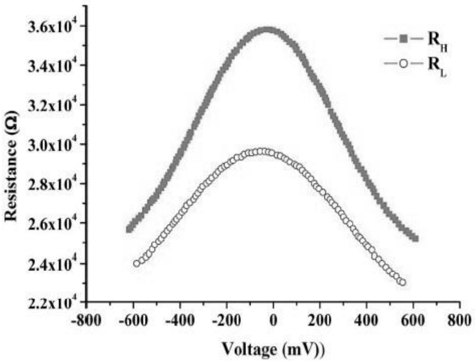
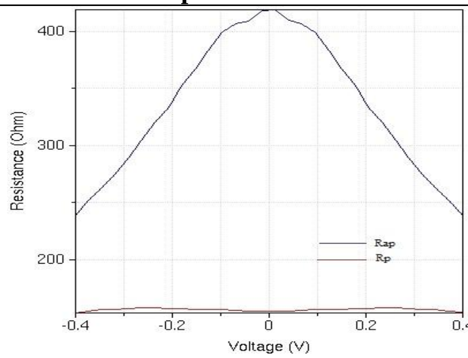
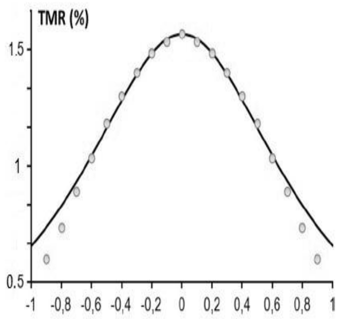
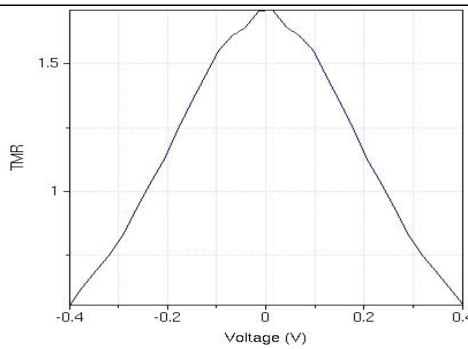
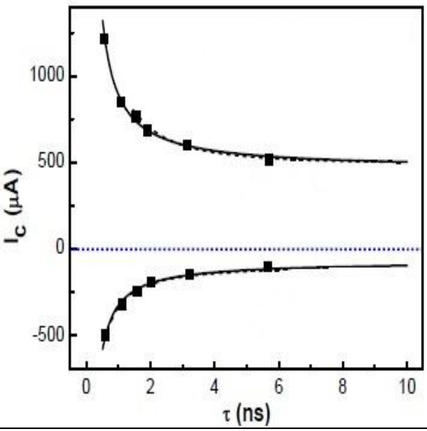
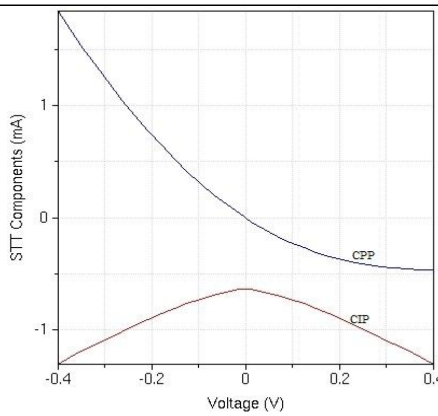


Figure 10. STT Component with applied voltage

The results of MTJ is also compared with previous work in Table 1. The results are compared in terms of resistance, TMR and STT Components. The performance shows that Proposed method has admirable performance in comparison of the similar work.

Table 1. Comparison of Results

Parameter	**Yao X et al.[20]**	**Proposed Results**
Resistance		
TMR		
STT Component		

V. Conclusions

All the previous reported literature of MTJ were not able to estimate the electrical properties accurately. In this paper, a novel modelling technique of MTJ has been offered to understand the properties by MTJ. The proposed method incorporates the electrical tunnelling concept with MTJ model characteristics. The approach uses the static magnetic field with low bias voltage and the spin transfer torque to measure the current effects in different plane. HSPICE simulations with MTJ LAB have been performed for basic logic computation. The experiment result are obtained for various logic circuits which have excellent TMR and current polarization value.

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