ENHANCEMENT OF MAGNETIC TUNNEL JUNCTION

Ajin.A.S*

F. Rajeena**

K.Swetha**

Abstract.

Modern MRAM typically employs Magnetic Tunnel Junctions (MTJs) as storage elements. The MTJ is a device based on quantum mechanical tunneling of spin-polarized electrons through a very thin insulator. The relative magnetization orientations of two ferromagnetic layers separated by this insulating layer determine the resistance of the MTJ structure. MRAM cells are designed to have two stable magnetic states that correspond to high or low resistance values, and to retain those values without any applied power. The cells are read by sensing the resistance to determine if the state is high or low. This resistance-based approach is distinctly different from commonly available commercial memories, such as DRAM and Flash memory that are based on stored charge. The present work has been carried out with an aim to improving the Free layer switching mechanism of MTJ. Switching speed distribution of the different free layer material compositions are compared by VSM analysis.

Keywords: **MTJ, switching speed of MTJ**

PACS: 85.75.-d

* Assistant Professor, Department of Physics, Asan Memorial College of Engineering & Technology.

** Department of Electronics & Communication, Asan Memorial College of Engineering & Technology.

INTRODUCTION

Magnetism contributes greatly to the goal of storing information for long time periods (15 years), in the form of hard disk drive and magnetic tape storage systems. In these two examples data access time is limited by the fact that these are mechanical systems. Solid state memories like Dynamic Random Access Memory (DRAM) and the Static Random Access Memory (SRAM) are capable of *ns* access times in both read and write operations. These memories are volatile and data is stored only as long as power is supplied to refresh the capacitor charge in DRAM and to keep the transistors ON in SRAM. The need for a non-volatile memory is reflected in the increasing demand for Flash memory, fuelled by its use in digital consumer products. However Flash technology suffers from slow write access time in the μs range and poor bit cyclability. Magnetic random access memories (MRAM) are one technology proposing to close the performance gap between the existing volatile and non-volatile memory technologies. The implementation of non-volatile memory elements in logic circuits could bring several major advantages such as instant on/off, built-in function programmability (in LUT, PLD or FPGA) and run time re-configurability. Reduction of power consumption and interconnection delay are the two other targets for very large scale integrated circuits (VLSIs). [1].

This paper is organized as follows; In First chapter the Conventional MRAM operation is described. The Second chapter is dealing about the ferromagnetic materials and the Third chapter is dealing with the Switching Speed Distribution of the Free layer by VSM analysis.

CONVENTIONAL MRAM OPERATION

The basic MRAM cell element consists of a Magnetic Tunnel Junction structure in which two ferromagnetic electrodes are separated by a thin insulating barrier.

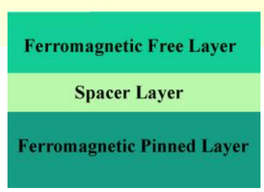

FIGURE 1. Basic structure of MTJ

Reading A Bit

To assess the bit state the bit resistance is compared to a reference value mid-way between the bit high (R_{high}) and low (R_{low}) resistance values. The inevitable resistance dispersion centered on R_{high} and R_{low} must be reduced since it impacts directly on the read margin. The bit resistance is determined by reading the current flowing through the tunnel junction at a fixed voltage. Typical read voltage values are 300mV, close to the voltage $V_{1/2}$ at which TMR drops to half its maximum low bias value and where maximum current variation is expected [2].

Spin Injection Write

Basic structure of the MTJ consists of three layers, upper Ferromagnetic Free layer with no fixed magnetization direction, middle tunnel barrier called Spacer Layer and a bottom Ferromagnetic Pinned layer with a fixed magnetization direction.

When a current is applied through this structure from bottom to top, all the out coming electrons from the Pinned layer are spin polarized in its magnetization direction. Then it will tunnel through the Spacer layer and finally reaches the free layer. Flow of spin polarized electrons switches the free layer in to the direction of pinned layer. Now both ferromagnetic layers are parallel then resistance across the device should be a small value.

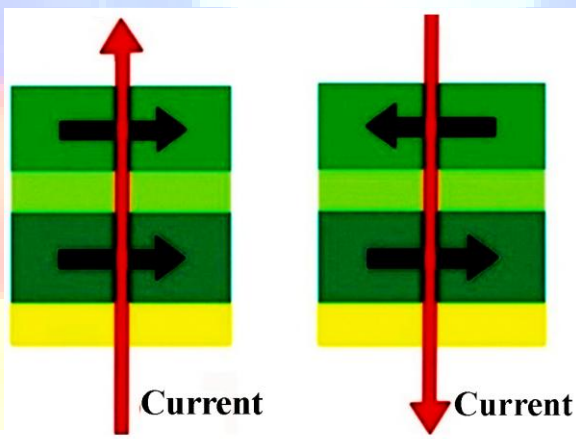

FIGURE 2. Magnetic orientations of the Free Layer

When current is reversed from top to bottom of the device, all the anti parallel spin electrons compared to the Pinned layer electrons cannot tunnel through the Spacer layer. This antiparallel electrons in the Free layer switches the free layer in to their spin direction. Now both the ferromagnetic layers having different magnetization direction then the resistance across the device should be a high value. These two values of resistance can be taken as binary ‘0’ and ‘1’ for storing bits.

Magneto Resistance

Magnetoresistance (MR) is the phenomenon described by the change in resistivity of a material due to the application of an external magnetic field. Later this phenomenon was known as Anisotropic Magnetoresistance (AMR).

Types of Magnetoresistance:

1.Giant Magnetoresistance (GMR)

2. Tunneling Magnetoresistance (TMR)

3. Colossal Magnetoresistance (CMR)

Among these TMR technology is utilized in modern MTJ.

Tunneling Magnetoresistance

An electron is having a wave like nature. When an electron is near to a potential barrier with energy greater than the energy of the electron, its spatial wave function can be nonzero within the barrier. If the barrier spans only a short distance, then the wave function may be non zero on the opposite side of the barrier as well. This is known as tunneling.

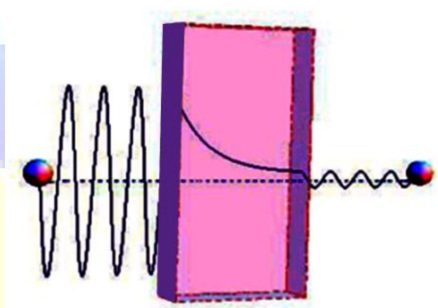

FIGURE 3. Quantum mechanical tunnelling through a potential barrier

In 1975, Michael Julliere discovered that if ferromagnetic materials were used as the conducting layers in such a junction, its conductance would depend on the magnitude of the applied field. The conductance between the two FM layers was proportional to the product of the densities of states of both FM electrodes. In a FM material, the density of states of one spin orientation is greater than the other at the Fermi surface. But in paramagnetic materials density of states of different spin orientation are same.

Fermi's Golden Rule states that electrons of a certain spin polarization can only tunnel to the other electrode if there are empty states of the same spin orientation. Thus, assuming that spin is conserved, if the FM magnetizations are oriented parallel to one another, minority spin carriers from one layer should fill the minority states of the other layer, while majority spin carriers fill majority spin states. This should result in an overall large conductance of the majority spin carriers, since the densities of states of both the electrodes are large.

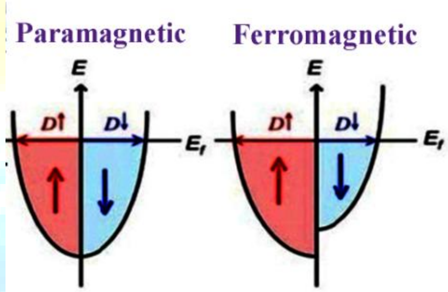

FIGURE 4. Density of states at the Fermi surface for different spin channels

On the other hand, when the layers are aligned anti parallel, the majority electrons from one electrode fill minority states in the other electrode, resulting in a highly attenuated current. That is resistance across this structure is very high [3].

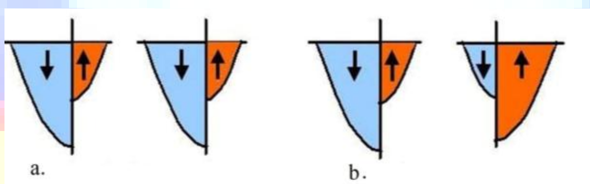

FIGURE 5. a. Low resistance path, b. High resistance path

FERROMAGNETIC DOMAINS

The magnetic moment of atoms in a ferromagnetic material cause them to behave something like tiny permanent magnets. They stick together and align themselves into small regions of more or less uniform alignment called magnetic domains or Weiss domains. Magnetic domains can be observed with a magnetic force microscope.

When a domain contains too many molecules, it becomes unstable and divides into two domains aligned in opposite directions so that they can stick together more stably. When exposed to a magnetic field, the domain boundaries move so that the domains aligned with the magnetic field grow. When the magnetizing field is removed, the domains may not return to an unmagnetized state. This result in the ferromagnetic material's being magnetized, forming a permanent magnet. When magnetized strongly enough that the prevailing domain overruns all others to result in only one single domain, the material is magnetically saturated. When a magnetized ferromagnetic material is heated to the Curie point temperature, the molecules are agitated to the point that the magnetic domains lose the organization and the magnetic properties they cause cease.

Magnetization Of Ferromagnetic Materials

Ferromagnetic materials exhibit magnetic properties even in the absence of an external field. Magnetization of the material is increased when an external magnetic field is applied to the specimen. The relationship between the magnetization (M) and applied field (H) is non-linear. The M-H graph shows hysteresis.

Applied field is increased to a positive value large enough to saturate the magnetization of the material (M_S), then reduced to a negative value large enough to produce saturation of magnetization in the reverse direction (- M_S), then increased back to zero once more. A symmetrical loop known as hysteresis is thus formed. The magnetization remains in the material when the applied field is reduced from saturation to zero is called Remanence (M_r). Size of the negative field required to reduce the magnetization to zero is called Coercivity (H_C).

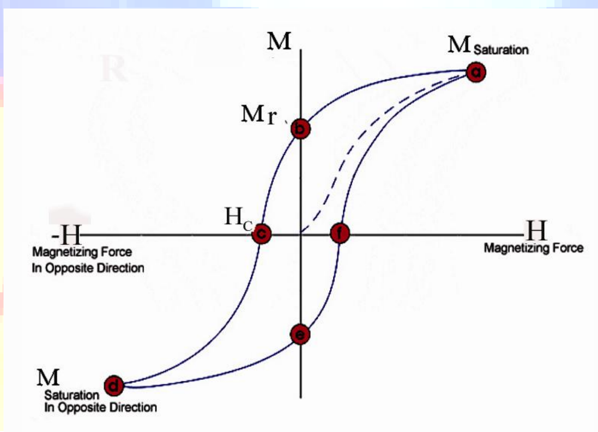

FIGURE 6. Hysteresis curve

The ferromagnetism in Fe, Co, Ni and Gd is mainly due to the self-alignment of groups of atoms carrying permanent magnetic moment in the same direction. The interaction between the neighboring atomic dipoles is very strong. It is called spin exchange interaction and is present even in the absence of an external magnetic field. Spontaneous magnetizations occur only below a certain temperature called ferromagnetic Curie temperature. Above the Curie temperature such materials behave like a paramagnetic material. Ferromagnetism is not exclusively characteristic of the crystal structure, it is arised from the electronic structure. The existence of partially filled *d* or *f* shell is essential in modern theories of ferromagnetism.

COMPARISON OF THE SWITCHING SPEED DISTRIBUTION OF FREE LAYER

One of the key parameter in the performance of magnetic tunnel junction is the switching field distribution (SFD), i.e., the dispersion of the field in the Free layer required to reverse the magnetization direction of individual grains. The SFD limits the overall performance in both longitudinal and perpendicular magnetic recording.

Magnetic materials can be divided into Hard and Soft magnetic materials. The process of magnetization consists of the movement of domain walls so that favourably oriented domains grow fast and the unfavourably oriented ones shrink. If the resistance to the movement of the domain wall is small, the coercive force is small and it is easy to magnetize the material. Such materials are called soft magnetic materials. If the resistance to the movement of the domain wall is large, the coercive force is large and the material is called hard magnetic material. Any crystal defects or imperfections in the film lead to a high hysteresis.

Soft or permeable materials have high permeability and low coercive force and are magnetized and demagnetized easily. Hard or permanent magnetic materials are used entirely for their ability to retain magnetic fields. Hence both a large coercive force and high residual induction are desirable to provide an adequate magnetic field from the magnet and to retain this field under adverse conditions. The permeability is low and a large magnetizing force is necessary to attain saturation magnetization of the material.

Soft magnetic materials are characterized by steeply ascending magnetization curve and high permeability's. Since the coercivity is low and the area of the loop is small. Hard magnetic materials are characterized by relatively large area of hysteresis loop of more or less a square shape. The materials with less coercivity can easily switches in a particular direction. In this section, we compared the coercivity of different FM layers. Using this comparison we can conclude which material is suitable for a Free layer. The materials with high remanence exhibits high noise margin.

Sample Preparation

Five different films are deposited for comparison. They are Cobalt (Co), Cobalt Iron Bilayer (CoFe), Cobalt Iron alloy (CoFe), Cobalt Iron Boron alloy (CoFeB). All the deposited films have 6nm thickness.

Co layer & CoFe Bilayer is obtained by Electron Beam Physical Vapor Deposition technique. 6nm Co layer is deposited over a silicon (100) substrate.For this, the deposition chamber is evacuated to a pressure of 10^{-7} Torr, with the help of a Rotary Pump and a Turbo Molecular Pump. Pressure is measured with the help of a Pirani guage. The material to be evaporated is in the form of ingots. The generated electron beam is accelerated to a high kinetic energy and focused towards the ingot. When the accelerating voltage is 5.42KV and the beam current is a few amperes, 85% of the kinetic energy of the electrons is converted into thermal energy as the beam bombards the surface of the ingot. The surface temperature of the ingot increases resulting in the formation of a liquid melt. Although some of incident electron energy is lost in the excitation of X-rays and secondary emission, the liquid ingot material evaporates under vacuum. The ingot itself is enclosed in a copper crucible, which is cooled by water circulation. The level of molten liquid pool on the surface of the ingot is kept constant by vertical displacement of the ingot. The evaporation rate is in the order of 0.1 A^0/sec.

For a 6nm CoFe Bilayer Initially 3nm thickness Fe film is deposited over a silicon (100) substrate. After that we replaced the Fe ingot by a Co ingot. Again starts deposition over the initially deposited Fe film. Thus we get a FeCo bilayer over Silicon.

CoFe alloy is deposited by dc sputtering system. In DC sputtering 1KV DC voltage is applied between the Silicon substrate (anode) and $Co_{50}Fe_{50}$ target (cathode). This voltage creates electron-ion plasma from the inert working gas Argon. The ionized gas gets accelerated into the $Co_{50}Fe_{50}$ target via the static field and transfers momentum to target atoms through these collisions. These atoms have enough energy to travel across the vacuum chamber and condense on the substrate into a film.

CoFeB alloy is deposited also by dc sputtering system. In this case diluted Boron is added along with $Co_{40}Fe_{40}$ target.

VSM Characterization

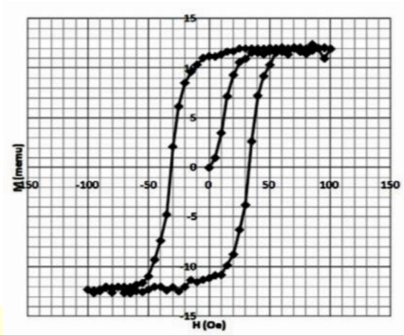

FIGURE 7. Co Single layer (6nm)

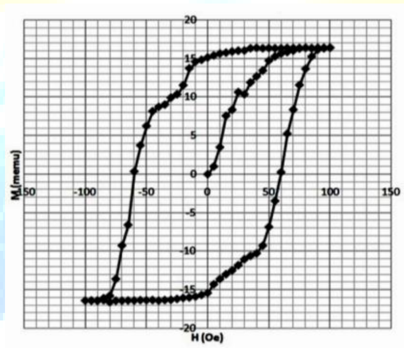

FIGURE 9. CoFe Bi layer (6nm)

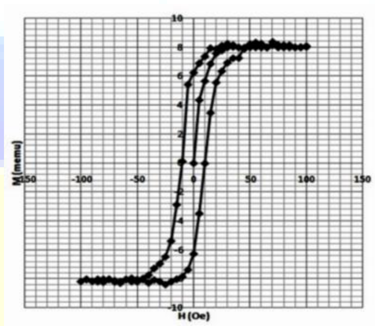

FIGURE 8. CoFe Sputtered layer (6nm)

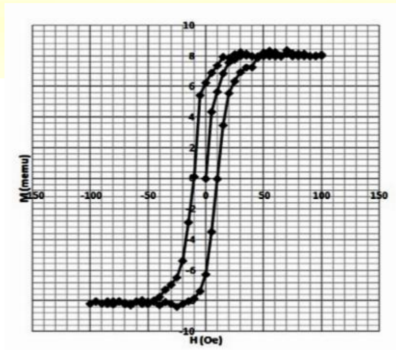

FIGURE 10. CoFeB Sputtered layer (6nm)

Results From The Analysis

TABLE 1. Comparison of the Magnetic properties of different Free Layers

Material composition	Depositing System	Thickness (nm)	Coercivity (Oe)	Field required for magnetic saturation (Oe)	Retetivity (memu)
Co	EB PVD	6	32	55	11.2
CoFe bilayer	EB PVD	6	60	85	15.1
CoFe alloy	DC Sputtering	6	10	40	6.2
CoFeB alloy	DC Sputtering	6	17	45	12.8

Switching speed of the Free layer largely depends on the coercivity of the ferromagnetic materials. From the VSM analysis we can calculate how much internal field is required for the complete switching of Free layer. From the table 1, we observe that the CoFe alloy requires only 40Oe internal field for a complete switching in a particular direction. After the addition of a diamagnetic material such as Boron along with this CoFe, it results in an increase in the retentivity. This will increase the data retention power of the memory element.

CONCLUSIONS

This experimental project focuses on enhancing the Free layer mechanism of MTJ. Free layer is a ferromagnetic layer whose direction of magnetic orientation is used to store information. From the results obtained from the VSM analysis it can be concluded that, 1. An alloy of CoFe which makes up the Free layer results in an increase in the switching speed. 2. The addition of Boron to the alloy of CoFe results in an increase in the noise margin.

ACKNOWLEDGMENTS

We wish to express our deep sense of gratitude and sincere thanks to our Principal **Dr. E. Chandrasekaran**, **B. Dhanalakshmi,** Head of the Department of Physics and **Dr.A. Sivagami,** Head of the Department of Electronics and Communication for their encouragement.

REFERENCES

1. R.C. Sousa, I.L. Prejbeanu, *Spintec (URA 2512 CEA/CNRS), 17 Rue des martyrs, 38054 Grenoble.*
2. J. Joshua Yang, A.K. Bengtson, C.X. Ji, D. Morgan, Y.A. Chang, *Sciencedirect received 22 october 2007; accepted 30 november 2007.*
3. Anuj Girdhar, *IEEE transactions on magnetics, 43, 2352 (2009).*
4. S.O.Pillai, *Solid state Physics.*
5. Alex Hubert, Rudolf Schafer, *Magnetic Domains The Analysis of Magnetic Microstructures.*
6. Frey, Hartmut, Khan, H. R.1st Edition. *Handbook of Thin Film Technology*
7. S. Diaz- Castanona,, J.C. Faloh-Gandarillaa, E. Munoz- Sandovalb, M. Terronesb, *Sciencedirect superlattices and microstructures 43 (2008) 482–486.*
8. Zheng Li, Jing Wang, Yuanhua Lin, and C.W.Nana, *Applied physics letters 96, 162505 2010.*
9. Chando Park, Lena Miloslavsky, Ira Lim, Sangmun Oh, Christian Kaiser, *ieee transactions on magnetics, vol. 45, no. 10, october 2009.*
10. Rene J. M. van de Veerdonk, Xiaowei Wu, and Dieter Weller, *ieee transactions on magnetics, vol. 39, no. 1, january 2003.*
11. E. Chen, D. Apalkov, Z. Diao, A. Driskill-Smith, D. Druist, D. Lottis, V. Nikitin, *ieee transactions on magnetics, vol. 46, no. 6, june 2010.*
12. Charles Kittel, A.J.Dekker *Introduction to solid state physics*