Voltage controlled low barrier nanomagnets for probabilistic bits

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by

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Certificate

This is to certify that the thesis titled **Voltage controlled low barrier nanomagnets for probabilistic bits** being submitted by **Abhinav Reddy Oruganti, Madhav Saini and Ayush** for the award of **Bachelor of Technology** in **Electrical Engineering** is a record of bona fide work carried out by him under my guidance and supervision at the **Department of Electrical Engineering**. The work presented in this thesis has not been submitted elsewhere either in part or full, for the award of any other degree or diploma.

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Abstract

Probabilistic bits (p-bits) implemented with low energy barrier nanomagnets (LBMs) have recently gained attention because they can be leveraged to perform some computational tasks very efficiently. Because of its instability, we chose to use them as similar to that of normal bits. p-bits are Low barrier nanomagnets similar to those of cells used in conventional memory technologies. We first demonstrated that current could be used to provide the required energy for the nanomagnet to switch the magnetization by 180^o. But because of their energy losses. We desired to use voltage to switch the magnetization of the nanomagnetic p-bit because on nanomagnets as the electric field generated would be high, the energy losses in switching the magnetization would be minimal. We then showed that applying alternating current (AC) and direct current (DC) voltage across a nanomagnet enables us to perform Read and Write operations. The results demonstrated that a voltage-induced magneto-electric field can be used to perform read and write operations on a nanomagnet.

Acknowledgments

We take this opportunity to express our gratitude to our mentor and advisor Professor Dhiman Mallick, whose support and guidance have been invaluable to us during this whole project. His suggestions have helped us think of creative and different approaches towards the problems we faced during our research and come up with various ways to solve those problems. Furthermore, we are grateful to Mr. Pankaj Pathak, PhD Scholar, for providing us with the right direction and assistance throughout the project. We also would like to thank the Electrical Engineering Department of IIT Delhi to give us the opportunity to do this research work in the incredible field of Nanomagnetic Devices.

Abhinav Reddy Oruganti, Madhav Saini and Ayush

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Chapter 1

Introduction

1.1 Motivation

Low barrier nanomagnets are used to make p-bits, which are similar to the cells can be used in traditional memory technologies. Extremely energy-efficient probabilistic computing is achieved using p-bits recorded in the magnetization states of low energy barrier nanomagnets (LBMs). P-bit systems can be used to solve some issues that would otherwise seem to need quantum computing. In addition, they may be used for binary stochastic neurons in stochastic machine learning. The p-bit can also be implemented in arrays to generate random numbers. They are extremely energy efficient, and it has been demonstrated that computing with p-bits excels at certain tasks, such as combinatorial optimization, invertible logic, and integer factorization. We used voltage sources for these unstable nanomagnets since previous research employing current sources had turned out to be energy-dissipating.

Chapter 2

Methodology

We have done the simulations on nanomagnet using the software mumax and subjected it to fields to get the desired outcomes. We employ a nanomagnet of thickness below critical thickness. The thickness below which the nanomagnets are unstable and rapidly oscillate is known as the critical thickness. Here, we are attempting to use unstable nanomagnets and explore their potential applications as p-bits. The simulations are run through mumax which uses these energy equations for unstable nanomagnets.

For the current source section of the paper, the simulations will solve the following equations and provide the desired output.

$$\frac{d\vec{m}(t)}{dt} = -\gamma \vec{m}(t) \times \vec{H}_{\text{total}}(t) + \alpha \left(\vec{m}(t) \times \frac{d\vec{m}(t)}{dt} \right) + a\vec{m}(t) \times \left(\frac{\eta \vec{I}_s(t) \mu_B}{q M_s \Omega} \times \vec{m}(t) \right) + b \frac{\eta \vec{I}_s(t) \mu_B}{q M_s \Omega} \times \vec{m}(t)$$

$$\hat{m}(t) = m_x(t)\hat{x} + m_y(t)\hat{y} + m_z(t)\hat{z} \qquad \left[m_x^2(t) + m_y^2(t) + m_z^2(t) = 1 \right]$$

$$\vec{H}_{\text{total}} = \vec{H}_{\text{demag}} + \vec{H}_{\text{thermal}}$$

$$\vec{H}_{\text{demag}} = -M_s N_{d-xx} m_x(t)\hat{x} - M_s N_{d-yy} m_y(t)\hat{y} - M_s N_{d-zz} m_z(t)\hat{z}$$

$$\vec{H}_{\text{thermal}} = \sqrt{\frac{2\alpha kT}{\gamma(1+\alpha^2)\mu_0 M_s \Omega(\Delta t)}} \left[G^x_{(0,1)}(t)\hat{x} + G^y_{(0,1)}(t)\hat{y} + G^z_{(0,1)}(t)\hat{z} \right]$$

Parameters	Values
Saturation magnetization (M_s)	$1.1 \cdot 10^6$
Gilbert damping (α)	0.01
Temperature (T)	300K
Major axis (a1)	80 nm
Minor axis (a2)	60 nm
Thickness (a3)	2nm and 4nm

Table 2.1: Parameters used in the simulations

For the paper's voltage source section, we computed the field that would appear across the nanomagnet and applied the relevant field across it, and ran simulations.

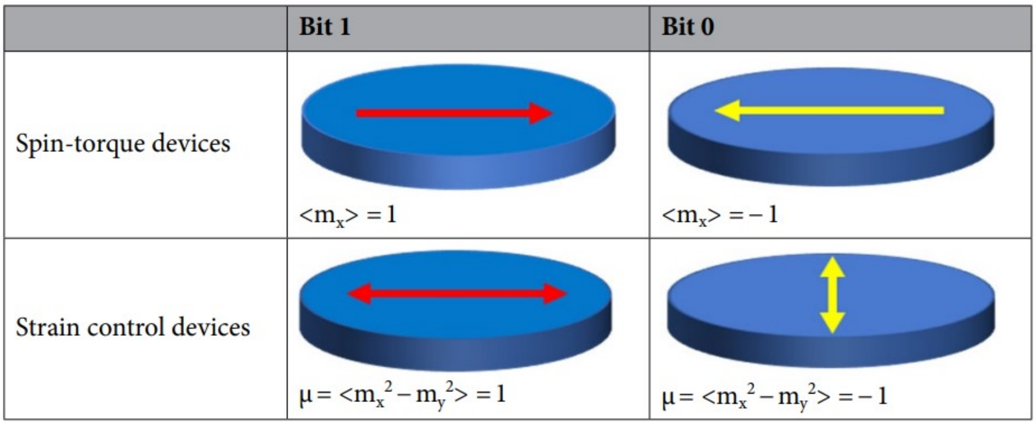

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Figure 2.1: The nanomagnets which are having easy axis in x direction store the bit information in the form of net magnetization m_x. We have defined a new Magnetization known as Pseudo-Magnetization

Pseudo-Magnetization $\mu = m_x^2 - m_y^2$. Here m_x and m_y the components of the magnetization along the x- and y- axis, respectively, and are normalized to unity ($m_x^2 + m_y^2 = 1$). As shown in the schematic diagram below. The bit state 0 and 1 are present.

The structure of the PE/FM nanomagnet is

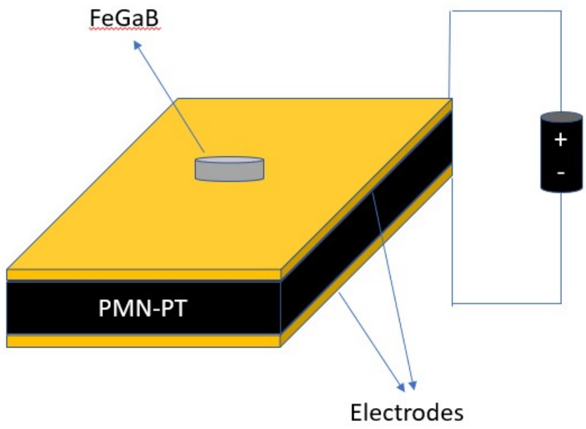


Figure 2.2: Schematic of magnetoelectric straintonic (STR) for READ operation (not-to-scale)

According to our theory and numerical simulations, the pseudo-magnetization can be manipulated by extremely low voltages, especially when the FM is designed as a low-barrier nano-magnet. One can define the energy expression associated with a PE/FM heterostructure as

$$E(Q,\mu)=\frac{1}{2C}Q^2 + Qv_m\mu - QV_{IN} - \left(\frac{E_A}{2}\right)\mu$$

where μ is the pseudo-magnetization that defines the easy-axis for the magnet $\mu = m_x^2 - m_y^2$, EA $=H_K\ M_s$ Vol./2 is the magnetic anisotropy that defines an easy-axis for the magnet, VIN is the applied voltage.

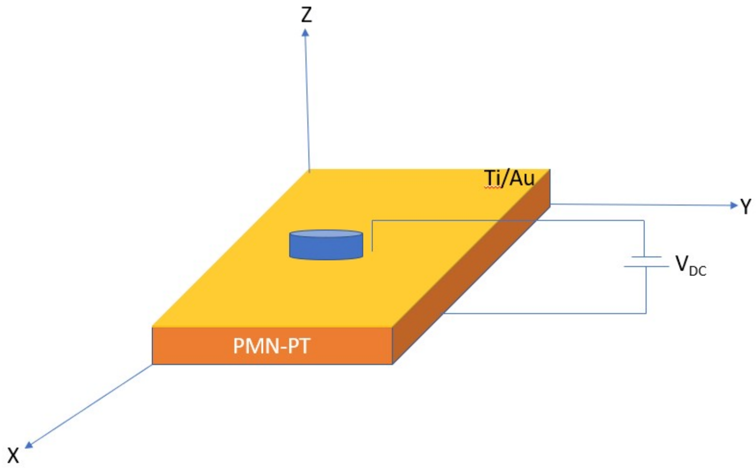


Figure 2.3: Schematic of PE/FM for WRITE operation (not-to-scale)

Since MuMax3 cannot use voltage directly, uniaxial constant axial anisotropy is used to replace Voltage which is connected with stress:

$$K_{u1} = \frac{3\lambda Y \epsilon}{2} \tag{2.1}$$

Here, ϵ is the in-plane anisotropic strain generated due to applied voltage across PMN-PT substrate given as follows:

$$\epsilon = (d_{01-1} - d_{100})\frac{V}{D} \tag{2.2}$$

where V is an applied voltage, and D is the thickness of PMN-PT substrate.

For READ operation, we had applied two different AC voltages 100V and 200V respectively.

FMR spectrum as a function of RF frequencies. FMR is an effective way to characterize voltage induced magnetization modulation in PE/FM heterostructures. By Applying a DC voltage across the PMN-PT substrate induces an anisotropic in-plane strain, which is transferred to the magnetic material. When the strain is large enough, the magnetic easy axis of the CoFeB layer rotates by 90 degrees, which is the magnetic WRITE operation.

By extracting FMR we have successfully extracted a strain-induced magnetic field H_s that modifies the magnetic easy-axis anisotropy.

In order to extract the voltage induced effective field using FMR measurements, we have derived a Kittel formula that includes a voltage induced stress term in the LLG equation.

$$f_{FMR} = \frac{\gamma\mu_0}{2\pi}\sqrt{(H_D + H_k + |H_{res}|)(H_k + |H_{res}|)}$$

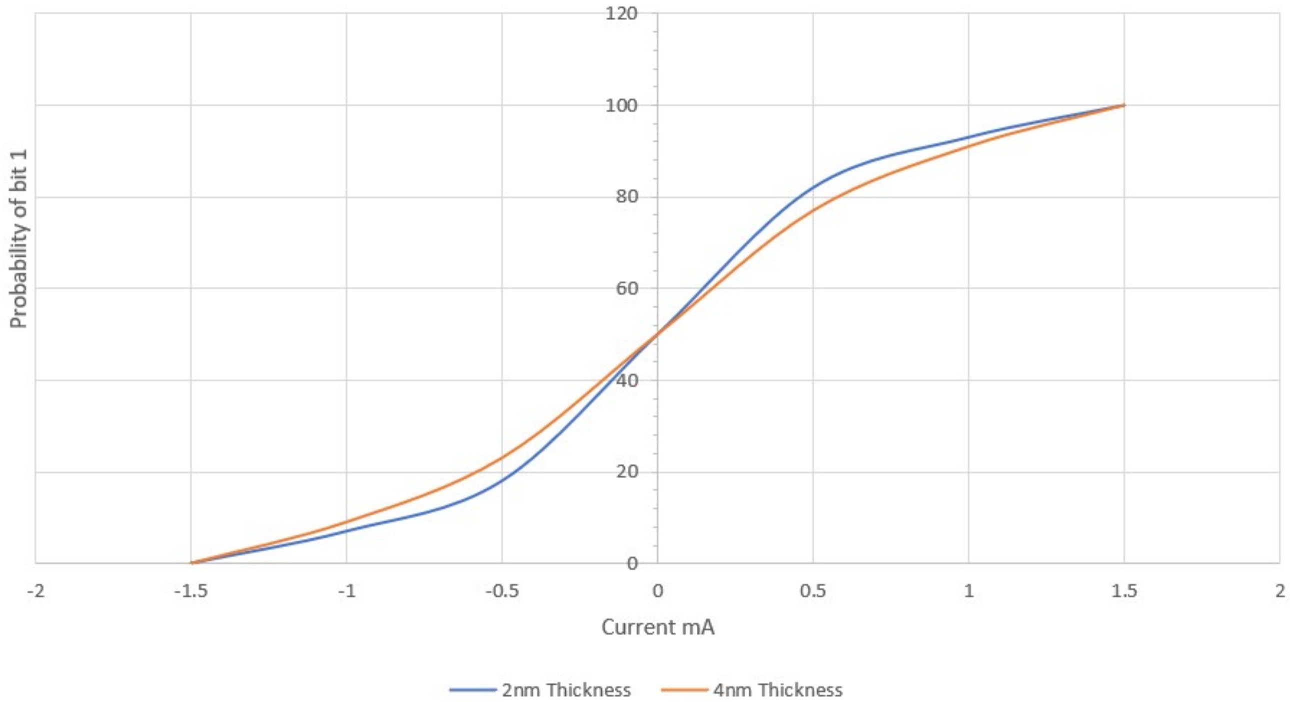
where where H_D is the demagnetizing field for the thin film and $\frac{\gamma}{2\pi}$ is the gyromagnetic ratio,H_k the magnetic anisotropy.

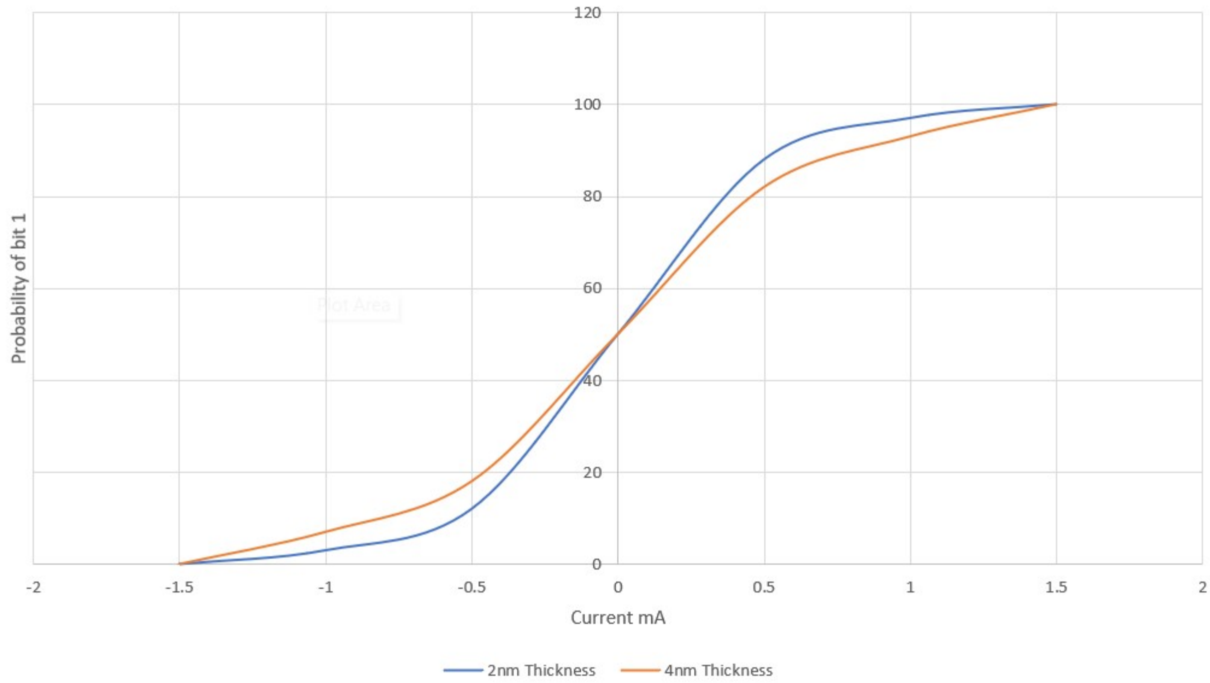
Using the FMR variation we differentiate the bits from 0 and 1.

We applied two different DC voltages of 100V and 200V for the WRITE operation.

Chapter 3

Results





120
100
80
60
40
20
0
-2
-1.5
-1
-0.5
0
0.5
1
1.5
2
Probability of bit 1
Current mA
2nm Thickness
4nm Thickness

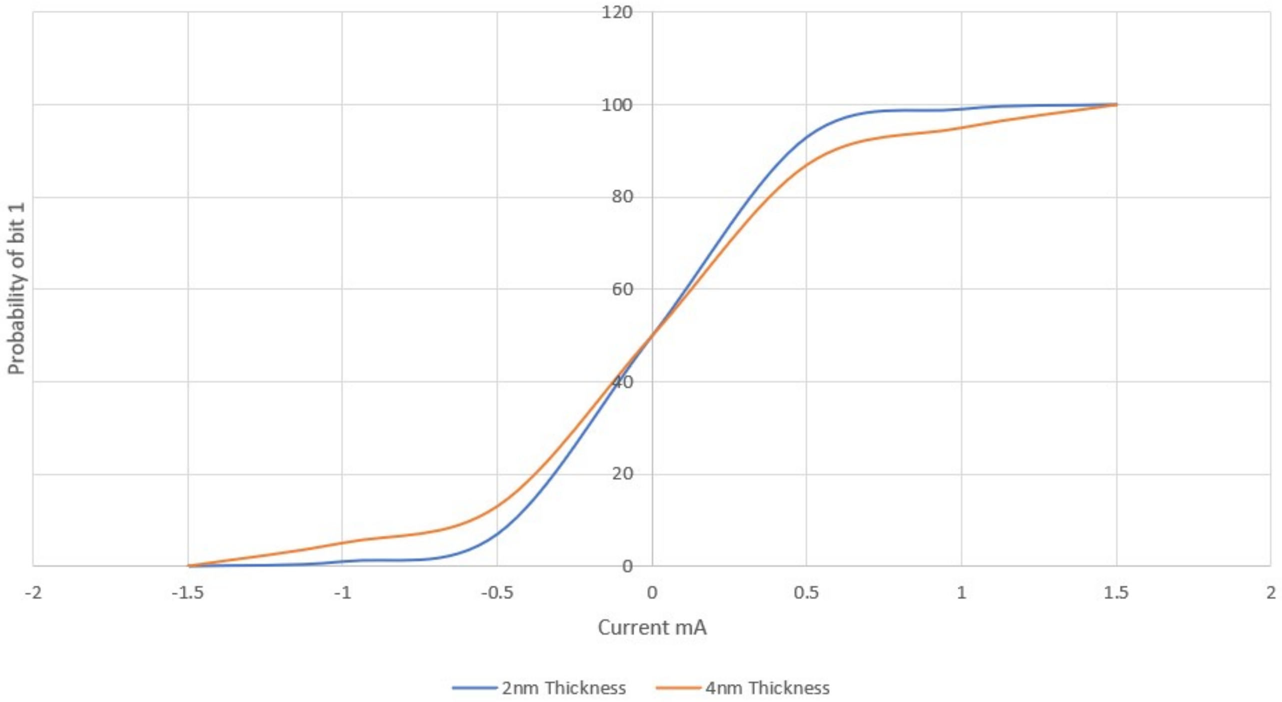
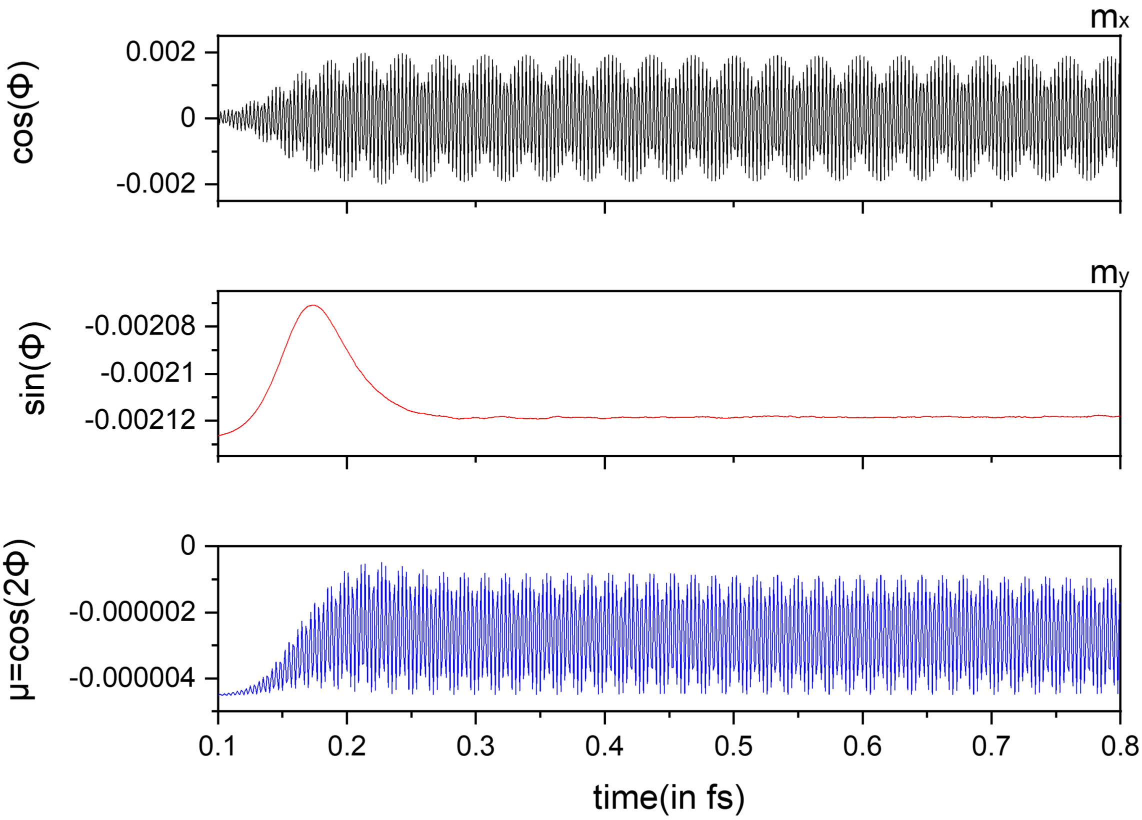


Figure 3.1: The Aspect Ratios are in the order of 1.1,1.5 and 2 respectively above. The major axis being fixed at 80nm and the minor axis dimensions are being varied. As the aspect ratio increases, the nanomagnets grow more elliptical; consequently, their tendency to flip also increases. Also. as current increases, the nanomagnets tend to align on the positive bit side.

The above results pertain to the current source, and initial uniform magnetization was applied to the nanomagnet. Then it inclines towards easy axis and then we are applying the current in direction of hard axis. We had used different aspect ratio, which is the ratio of major to minor axis. We used two different thickness which are below critical thickness to observe the distinction in behavior.


mx
cos(Φ)
0.002
0
-0.002
my
sin(Φ)
-0.00208
-0.0021
-0.00212
μ=cos(2Φ)
0
-0.000002
-0.000004
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
time(in fs)

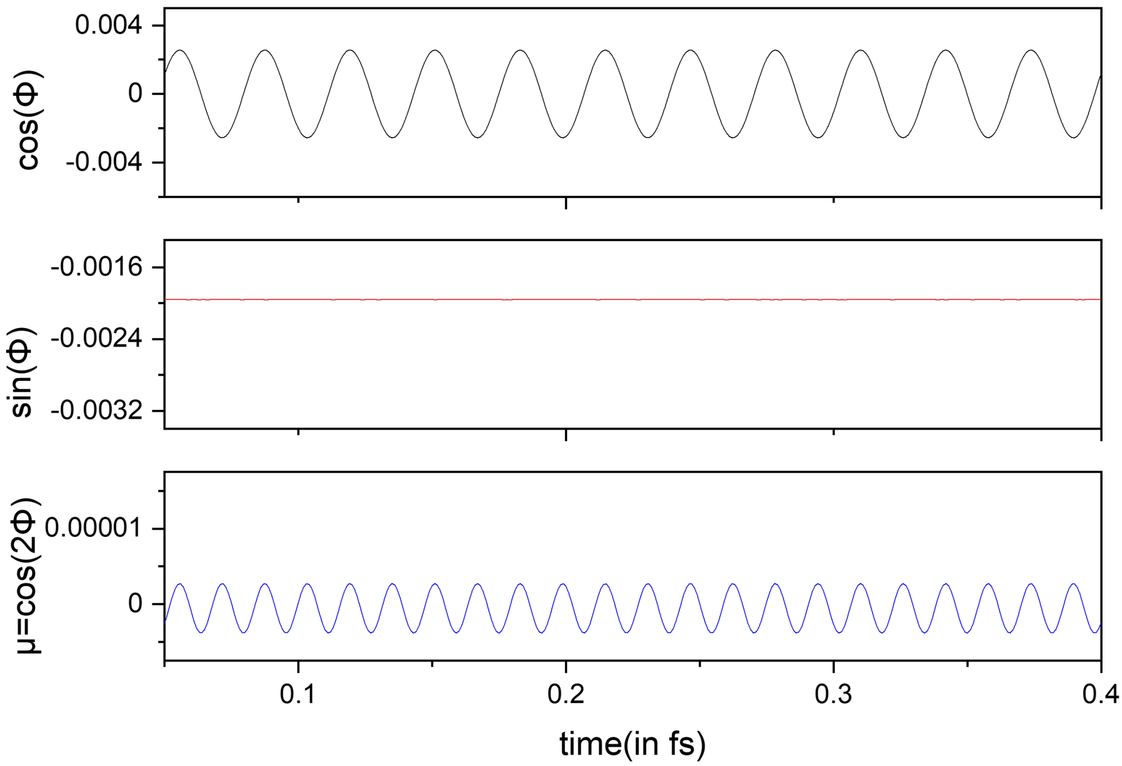


Figure 3.2: The statistics presented above pertain to the WRITE operation for two distinct voltages, 100V and 200V, respectively.. The pseudo-magnetization can be differentiated between two states when two voltages of 100V and 200V are applied across the structure in (Fig 2.2) from above two figures. Thus, one can be considered 0 and the other 1. We realize that we can distinguish in μ(pseudo-magnetization) by applying various voltages which enables us to write the bits.

After READ operation, for WRITE operation we have applied two different voltages are and then the corresponding FMR is plotted for WRITE operation.

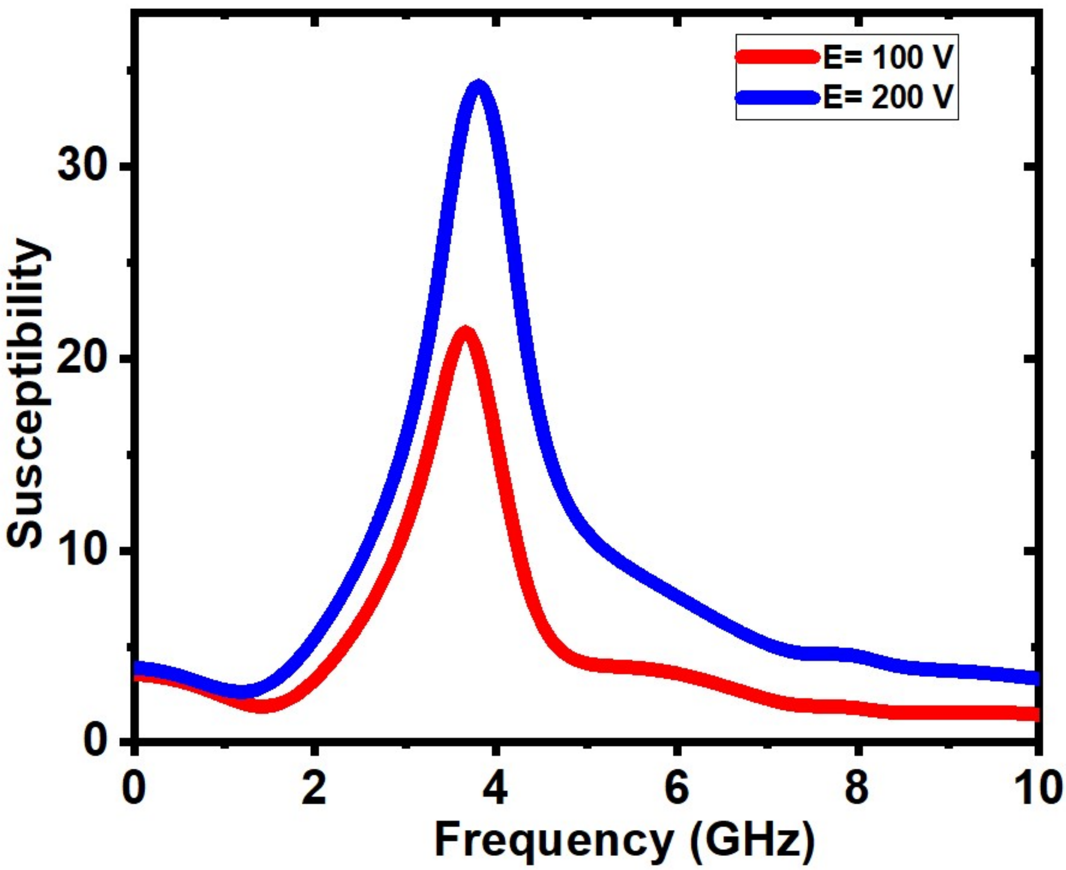


Figure 3.3: FMR is plotted for 100V and 200V for READ operations. As discussed above, when DC voltages are applied, the magnetic anisotropy of CoFeB film is modulated by the strain induced in the PMN-PT film (in Fig. 2.3) and the resonance frequency of FMR changes accordingly. RF field frequency with different DC magnetic field when V_{DC} = 100V and 200V, we can see from the difference in peaks that when AC voltage is applied, the resonance moves to the right.

Through this we are able to define distinct bits, which the FMR spectrum allows us to see and read as distinct bits.

Chapter 4

Conclusions and Scope

We had implemented simulations on the unstable nano-magnets(whose thickness is less than that of critical thickness) and our aim is to use p-bits which can be used to invent new energy-efficient devices. We chose elliptical devices as opposed to circular devices because circular devices have two easy axes, compared to that of elliptical devices where the major axis(a) is considered as easy axis and minor axis is hard axis(b), making it easier to distinguish between the two and designate one direction as 0 and the other as 1. We switched from the current point of view to voltage because of the incorporated energy looses.

We demonstrated that the READ and WRITE operation for the voltage source can be accomplished by simulating a field across the nanomagnet when a voltage is applied across it. As shown in above Fig 3.3, the FMR spectrum we had applied two different voltages (100V and 200V). Consequently, we are able to use the voltage for READ-WRITE operation using voltage through simulations.

Scope for Future Work: For, future works we can find the power consumption and compare with that of current's behavior. And further optimize it and clearly observe the behavior of the nano-magnet and find the corner cases where it fails to work. The theoretical work presented here indicates that the novel ME memory device proposed is feasible and can be incorporated into future energy-efficient devices. Much more research can and will be done in the future on this interesting phenomenon.

Bibliography

[1] R. Faria, K. Y. Camsari and S. Datta, "Low-Barrier Nanomagnets as p-Bits for Spin Logic," in IEEE Magnetics Letters, vol. 8, pp. 1-5, 2017, Art no. 4105305, doi: 10.1109/LMAG.2017.2685358.

[2] Kerem Y. Camsari, Brian M. Sutton, Supriyo Datta (2019). p-bits for probabilistic spin logic. Applied Physics Reviews, 6(1), 011305. https://doi.org/10.48550/arXiv.1809.04028

[3] J. L. Drobitch and S. Bandyopadhyay, "Reliability and Scalability of p-Bits Implemented With Low Energy Barrier Nanomagnets," in IEEE Magnetics Letters, vol. 10, pp. 1-4, 2019, Art no. 4510404, doi: 10.1109/LMAG.2019.2956913.

[4] Shen, T., Ostwal, V., Camsari, K.Y. et al. Demonstration of a pseudo-magnetization based simultaneous write and read operation in a Co60Fe20B20/Pb(Mg1/3Nb2/3)0.7Ti0.3O3 heterostructure. Sci Rep 10, 10791 (2020). https://doi.org/10.1038/s41598-020-67776-y

[5] P. Pathak and D. Mallick, "Straintronic Nanomagnetic Logic Using Self-Biased Dipole Coupled Elliptical Nanomagnets," in IEEE Transactions on Magnetics, vol. 58, no. 10, pp. 1-6, Oct. 2022, Art no. 3401406, doi: 10.1109/TMAG.2022.3199589.

[6] P. Pathak and D. Mallick, "Size-Dependent Magnetization Switching in Magnetoelectric Heterostructures for Self-Biased MRAM Applications," in IEEE Transactions on Electron Devices, vol. 68, no. 9, pp. 4418-4424, Sept. 2021, doi: 10.1109/TED.2021.3088079.