Neuromorphic devices for AI/ML

Project Report
IIT Hyderabad

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1 STT Switching Dynamics by varying the shape Anisotrop

1.1 Abstract

Spin Transfer torque magnetic random-access memory (STT-MRAM) stands out as a promising technology for non-volatile memory applications due to its remarkable characteristics such as high speed, low power consumption, and robustness. This study focuses on simulating an STT-MRAM stack, comprising a fixed layer, spacer, and free layer, with explicit modeling of only the free layer's magnetization on a 2D grid. We investigate the impact of varying the dimensions of the free layer solely along the Y-direction, while keeping the other two dimensions constant, thereby altering the shape anisotropy of the grid. Additionally, we maintain other parameters, such as the fixed layer's polarization and spacer layer properties, at constant values. Through this simulation, we observe the switching time for different current values in milliamperes. The obtained results shed light on the influence of free layer size and current density on the switching dynamics of STT-MRAM. These insights are crucial for enhancing device performance and reliability in practical applications

1.2 Origin of the problem

Spin-transfer torque magnetic random-access memory (STT-MRAM) is renowned for its superior speed compared to other memory devices. However, to fully leverage its potential, optimizing the switching speed of STT-MRAM becomes imperative. To address this challenge, we employ the micromagnetic simulation software mumax3 to further enhance the switching speed of STT-MRAM.

In this pursuit, we focus on systematically adjusting the layer parameters of the free layer in STT-MRAM devices. By simulating the impact of variations in currents, we aim to explore how changes in layer dimensions influence the switching speed of the spin in STT MRAM. The crux of the problem lies in identifying the optimal configuration of layer parameters that maximizes the efficiency of STT current while minimizing the magnitude of write currents necessary for reliable magnetization switching. By elucidating the effects of dimension variations on write currents, we seek to provide valuable insights for the design and development of STT-MRAM devices with significantly improved switching speed and energy efficiency.

1.3 Relevance in the area of memory/neuromorphic devices.

MRAM's non-volatile storage capabilities enable it to retain data even without a power source, eliminating the necessity for a constant power supply. This feature renders MRAM well-suited for power-efficient applications like neuromorphic computing systems. Alongside its ability to provide rapid access to stored data with fast read/write speeds, MRAM exhibits high endurance, ensuring durability for repeated operations throughout its lifetime. Collaboration between NXP Semiconductors and TSMC underscores MRAM's integration into automotive systems, particularly in software-defined vehicles. Its fast read/write times and reliability minimize downtime associated with software updates, enhancing efficiency in automotive processing.

Moreover, MRAM's properties position it favorably for neuromorphic computing applications, where it can efficiently store synaptic weights and configurations. This capability enables the low-power implementation of neural network models, facilitating tasks such as pattern recognition and inference. Advancements in semiconductor manufacturing, notably with spin torque transfer MRAM (STT-MRAM), have led to improvements in memory performance and density. These advancements contribute to the scalability and seamless integration of MRAM in memory and neuromorphic devices, further extending its utility and applicability across various technological domains.

1.4 Methodology followed/to be adopted.

Understanding mumax3:
Familiarize yourself with the mumax3 software interface, its commands, and its documentation.
Learn how to set up simulations, define materials, and specify simulation parameters.

Initial Simulations without Parameter Changes:
Set up a simulation of the STT MRAM without modifying any parameters.
Run the simulation to observe the default behavior of the system. Analyze the results to understand the baseline performance of the STT MRAM.

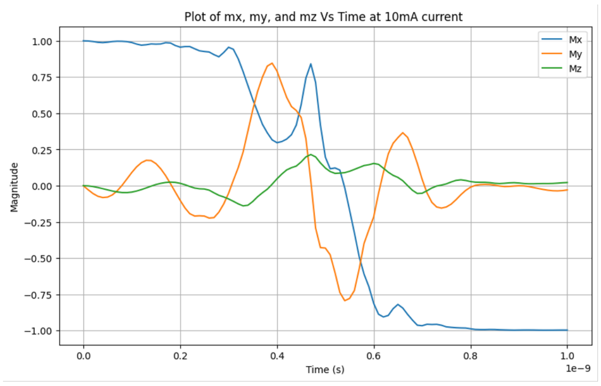
Varying Y-Dimensions for Shape Anisotropy: Modify the y-dimensions of the system to introduce shape anisotropy. Run simulations with different y-dimensions to observe how changes in geometry affect the behavior of the free layer.
Analyze the results to understand the impact of shape anisotropy on the performance of the STT MRAM.

Varying Current: Adjust the current density parameter to vary the current flowing through the system.
Run simulations with different current densities to gain insights into the behavior of the free layer under varying current conditions.
Observe changes in magnetization dynamics, such as precession and switching behavior, as the current density is varied.

Modeling the Spin-Torque MRAM Stack: Ensure that the spin-torque MRAM stack is accurately represented in the simulation.
Define the properties of the fixed layer, spacer layer, and free layer as per the specifications of the STT MRAM device.
Model the magnetization of the free layer using a 2D grid.

1.5 Result

X = 160nm, Y = 40nm ,Z =5nm



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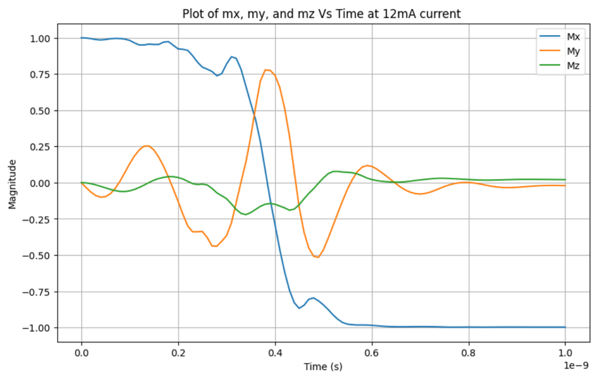

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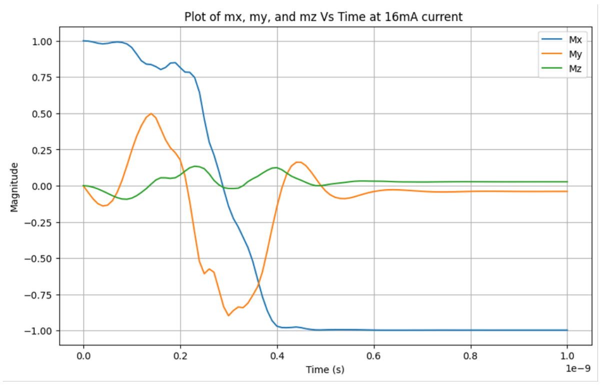

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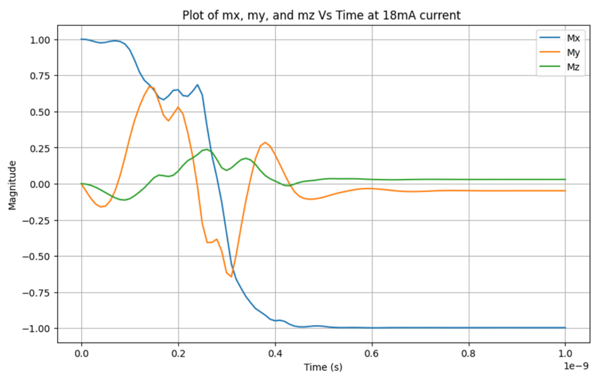

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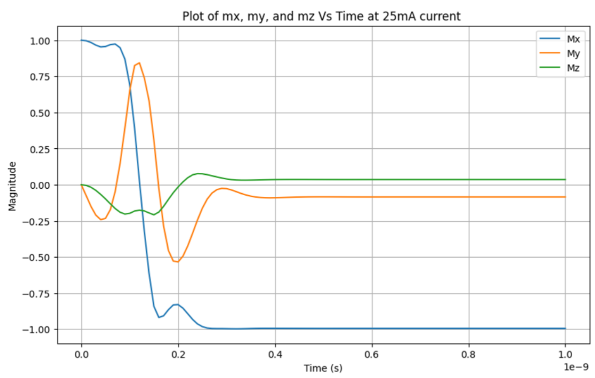

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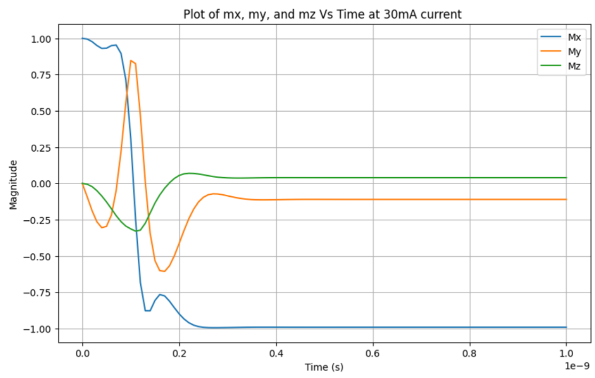

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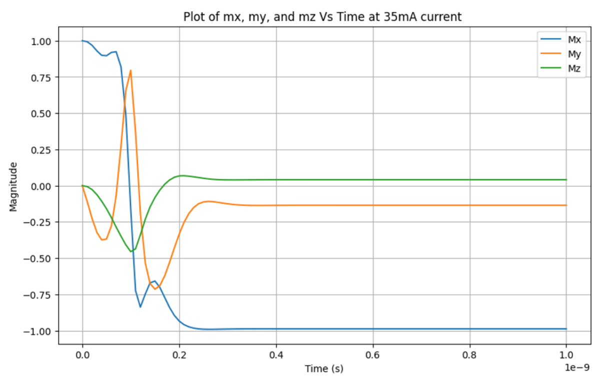

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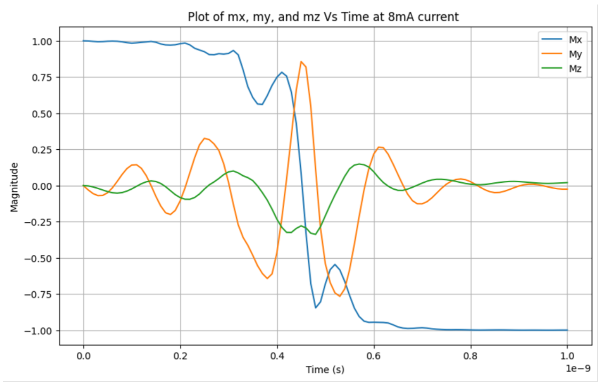
X = 160nm, Y = 60nm ,Z =5nm



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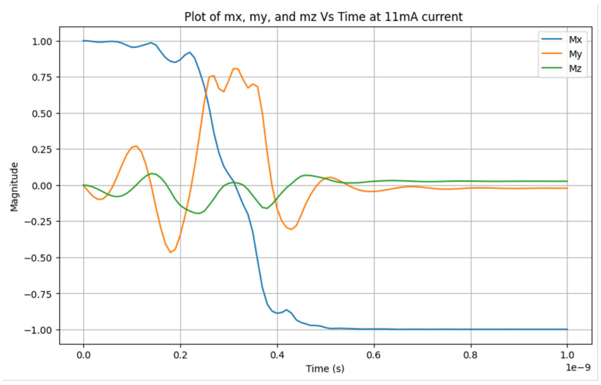

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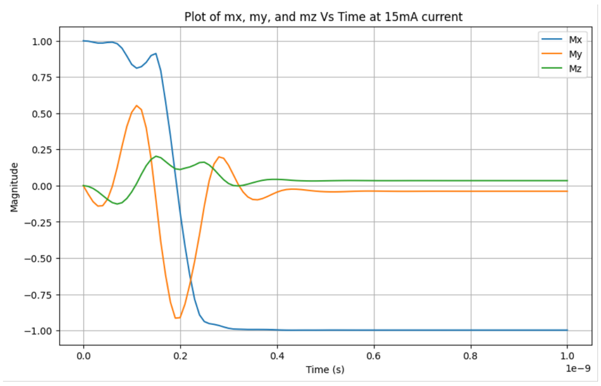

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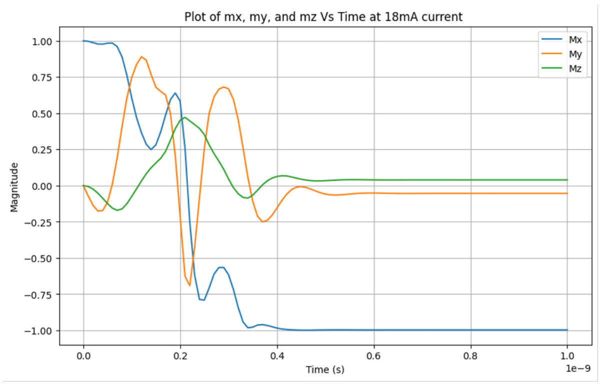

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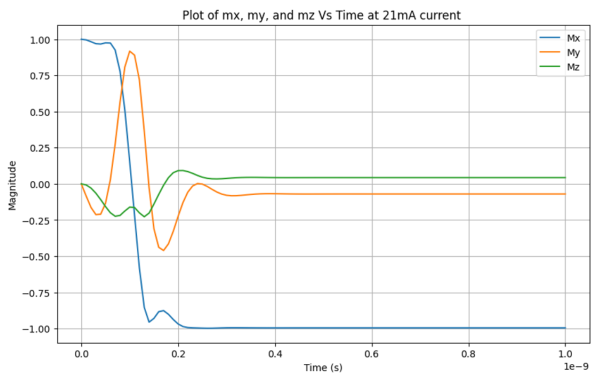

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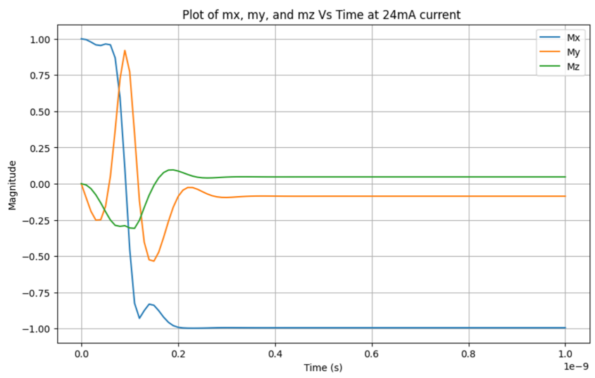
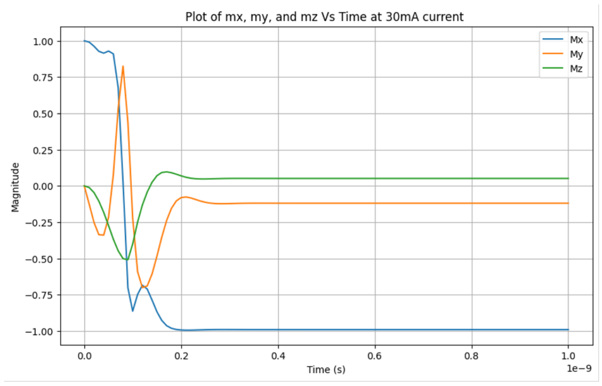


Figure 1.13:

X = 160nm, Y = 80nm ,Z =5nm



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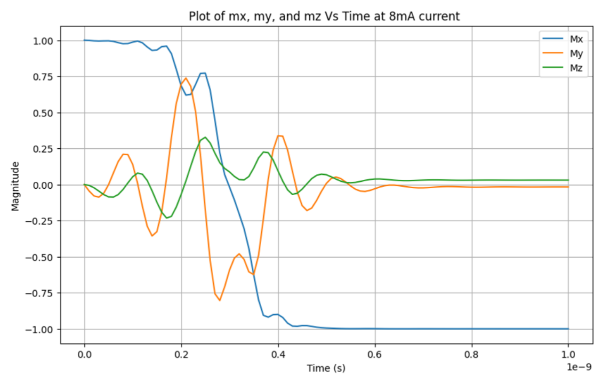

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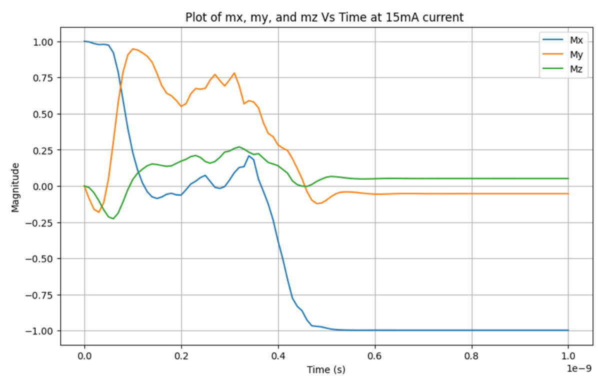

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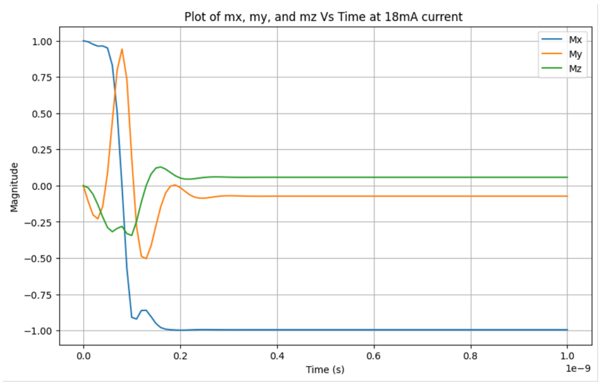

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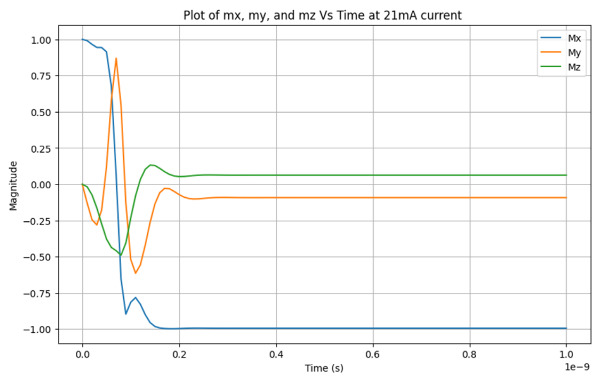

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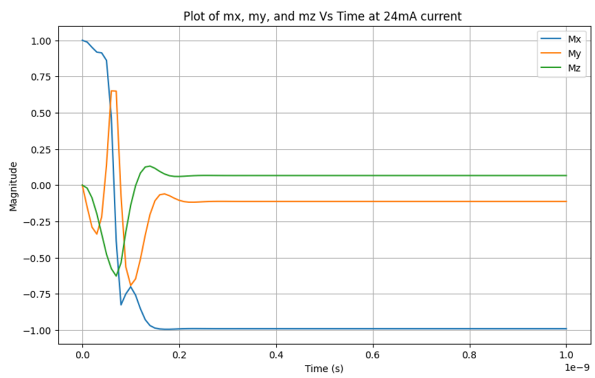

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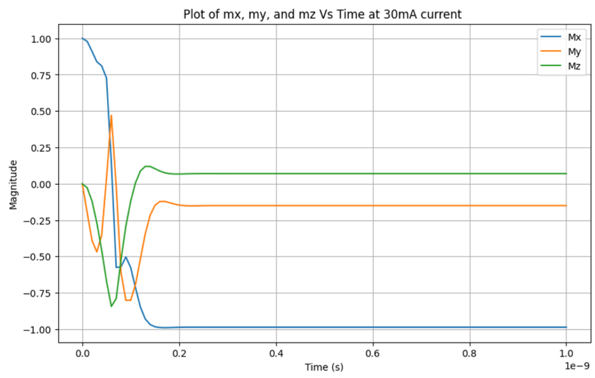

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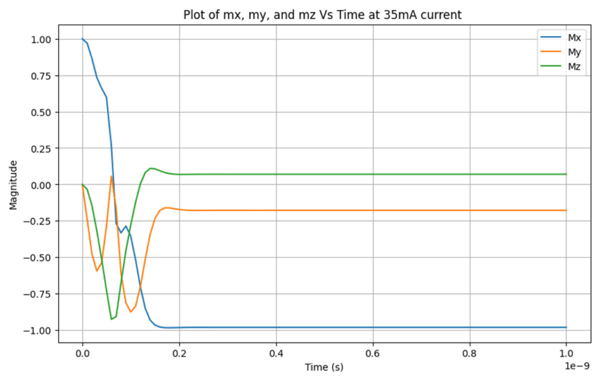

Figure 1.21:

1.6 Conlusion

KEY PARAMETERS	VALUE
X- DIMENSION	160 nm
Y- DIMENSION	Variable – [40nm, 60nm, 80nm]
Z- DIMENSION	5 nm
POLARISATION OF CURRENT	0.5669
POLARISATION ANGLE OF FIXED LAYER	20 degree
MAGNETISATION SATURATION	8 M amp/m
OPTIMAL POINT OF OPERATION (Y = 40nm)	18mA to 22mA Switching speed (80p seconds)
OPTIMAL POINT OF OPERATION (Y = 60nm)	20mA to 25mA Switching speed (100p seconds)
OPTIMAL POINT OF OPERATION (Y = 80nm)	25mA to 30mA Switching speed (120p-150p seconds)

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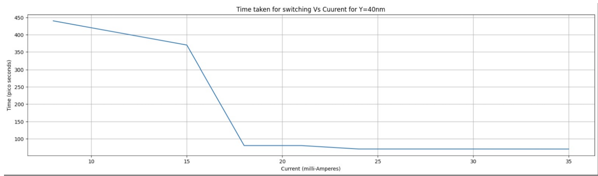

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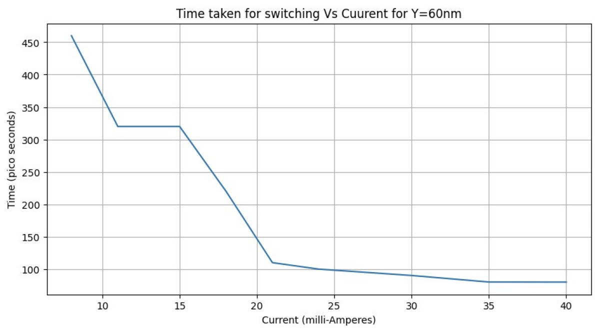

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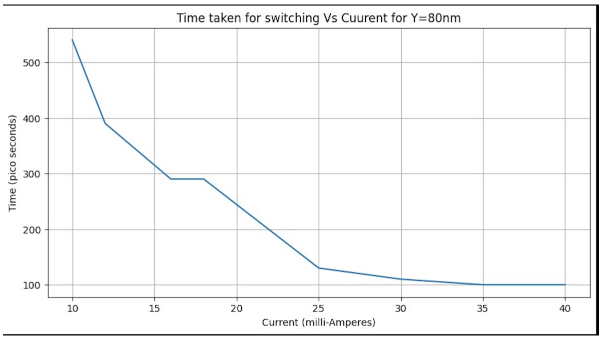

Figure 1.25:

1)We observe an increase in the switching speed of the spin with an increase in current for all varied Y-dimensions, i.e., 40nm, 60nm, and 80nm.

2)With an increase in the Y dimension from 40nm to 80nm while keeping the current constant, we observe that the switching speed slightly increases. This is due to shape anisotropy.

3)To improve device performance, we need to operate at a point where both speed and current are optimal, i.e., we need to operate at low currents while achieving high speed.

4)For the free layer with dimensions (160nm, 40nm, 5nm), the MTJ cell operates efficiently at a current of around 18mA to 22mA, resulting in a switching time of approximately 80 picoseconds.

5)For the free layer with dimensions (160nm, 60nm, 5nm), the MTJ cell operates efficiently at a current of around 20mA to 25mA, resulting in a switching time of approximately 100 picoseconds.

6)For the free layer with dimensions (160nm, 80nm, 5nm), the MTJ cell operates efficiently at a current of around 25mA to 30mA, resulting in a switching time of approximately 120 picoseconds to 150 picoseconds