Control of Interfaces in Magnetic Tunnel Junctions

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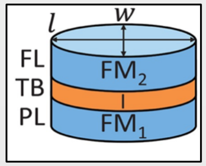
Magnetic Tunnel Junctions

Magnetic tunnel junctions, or MTJs an arrangement of a ferromagnetic material, like iron or cobalt, placed on the opposing sides of a thin insulating layer, the latter being based on oxides of nonmagnetic metals, such as magnesium oxide, MgO. The MTJ can range in material type, size, shape, as well as many other parameters, but must contain those three elements. Magnetic tunnel junctions rely on a few key principles from condensed matter physics for their operation, like spin dependant tunneling, a phenomenon in which electrons tunnel through the insulating layer of the MTJ. It is important to optimize these junctions for efficiency and power consumption, since at large scales, smaller losses add to considerable bulk inefficiencies, so understanding the efficiency is vital.

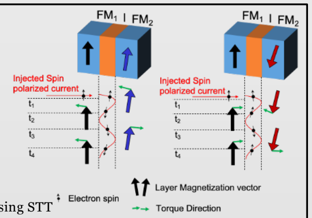


Example Diagram of MTJ

Controlling MTJs

Another key piece of physics needed to the control and operation of MTJs is the presence of Spin Transfer Torque (STT). Normally when electrons flow causing current, the number of spin up and spin down electrons that flow is equal, resulting in a net spin of zero. In STT, a spin-polarized current can pass some spin angular momentum to the magnetization of the ferromagnetic resulting in a change in the magnetization. Using the spin-polarized current to alter the magnetization changes the resistance across the junction. The following equation describes the spin transfer torque.

$$\frac{d\vec{M}}{dt} \propto -\vec{M} \times (-\vec{M} \times -\vec{H})$$



Controlling Magnetization using STT

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Efficiency of Junctions

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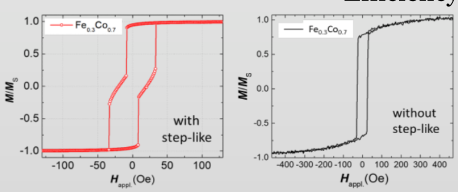
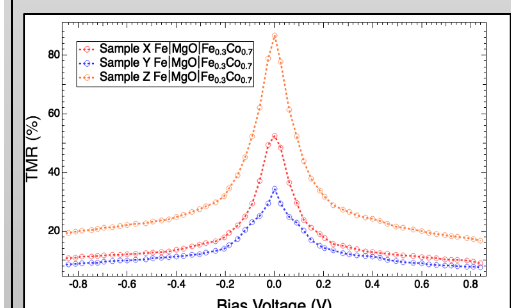
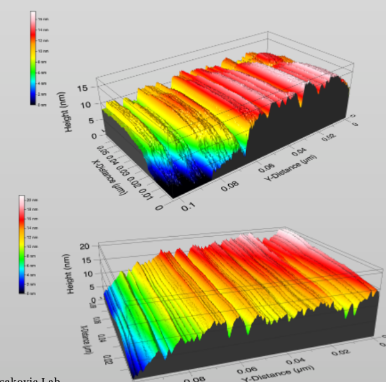


Hysteresis loops of of magnetic tunnel junctions grown with stepped faces (left) and approximately smooth flat barriers (right)

The energy required to operate these junctions is also directly proportional to the product of the magnetization and the applied magnetic field, which is proportional to the product of the areas of the hysteresis loop created by the junction, shown on the left. By altering and controlling the shape and size of the loop, the efficiency of the junction can be explored and optimized. It can be seen that by introducing step like features, the bulk magnetic properties of the MTJ are changed, and the overall energy to operate the junction is smaller, shown by the are of the curves.

Results





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Tunneling Magnetoresistance vs. Bias Voltage for three different devices. Each device sample is made to be of the same size, material, and shape, while the difference lies in the stepping of the tunneling barrier. A higher TMR indicates more electrical control due to heightened magnetic anisotropic effects as a result of more etched steps and steeper etched slopes.

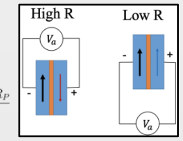
AFM images of the surfaces of junctions show the areas that exemplify patterning and steps. The top image shows a relatively flat slope with some dips along the surface, while the lower image shows a steeper slope with finer steps that are shallower. Comparing the AFM and transport data, the top sample, with the flattest slope, shows the lowest TMR, peaking around 40% when there is no bias voltage, compared to the TMR of the bottom junction, which peaks at over 80% at the same bias voltage.

Tunneling Magnetoresistance

An important metric to characterize MTJs is the Tunneling Magnetoresistance (TMR). The TMR is a measure of the relative electrical resistance between the two extreme states of the magnetizations of the ferromagnetic layers. The parallel state is when the direction of magnetizations are perfectly aligned, and the electrical resistance is low, while for anti-parallel the magnetizations are opposing and resistance is high. The TMR for a magnetic tunnel junction can be given by the equation:

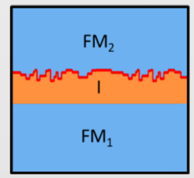
$$\mathrm{TMR} = \frac{R_{AP} - R_P}{R_P}$$

Tunneling Magnetoresistance shows how much electrical control is had over the junction, and how much differentiation is had between the two states. The reason the resistance changes as a function of the magnetization is due to spin-dependent tunneling. The intrinsic spin that each electron combined with the polarizing effect had by the magnetic effects of the junction determines the number of electrons that pass through, and in turn the current across the junction.



Resistance of an MTJ with the changing orientation of magnetization

Lithography



Cross-section of MTJ with a stepped insulating layer

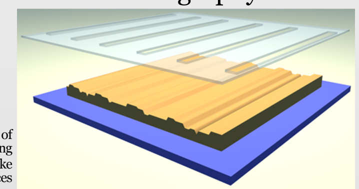


Diagram of sputtering used to make MTJ interfaces

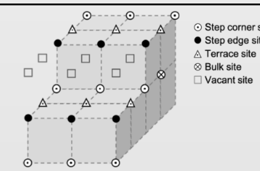


Diagram of vacant and full lattice sites that contribute to magnetic anisotropy

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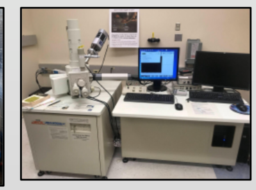
Some of the Methodology

Both Scanning Electron Microscopy (SEM) and Atomic Force Microscopy (AFM) were used to get images of the arrays of junctions and individual junctions respectively. SEM provides images that show the arrays of junctions, as well as see any potential defects in the junctions. Looking at junctions allows the comparison with current models based on junction relative shape and size. AFM imaging focuses on individual junctions surfaces, and will highlight features of the ferromagnetic layers and tunneling barriers.

Quantitatively, various aspects of the devices can be characterised by measuring the transport properties. It is important to measure the Tunneling Magnetoresistance as both a function of applied voltage and as applied magnetic field. This allows the comparison of the etched surfaces to the values that describe the efficiency of the MTJs.

Sample Stage of AFM used to image surfaces of junctions



Scanning Electron Microscope used to take larger images of junction arrays

Ongoing and Future Work

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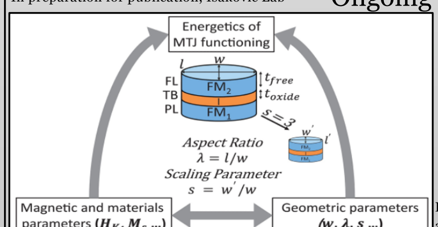

Examination of MTJ parameters that affect the scaledown of junctions

In order to further study magnetic tunnel junctions, current models have to improve to support scaling junctions down to smaller length scales. Other parameters like aspect ratio as a function of total junction size must also be considered and further explored. While the nanoengineering of these MTJ interfaces shows promising results in terms of scalability and energy efficiency, much more work is needed for full confidence in lithographic and manufacturing methods to start larger spintronics based devices.

Conclusions

This project proposed and tested cost-effective nanofabrication methods for controlled interfaces between layers of MTJs. The correlation between properties of the tunneling barrier, step density and slope, and the TMR coefficient were explored and observed. Current and ongoing work also looks at the effects of scaling on energy efficiency and optimization in magnetic tunnel junctions.

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