Energy Efficient Magnetic Tunnel Junctions

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We introduce magnetic tunnel junctions (MTJs) as a nanodevice of interest to spin-based information storage. Specifically, we work with MTJs that use spin transfer torque (STT). Our specific task is understanding the energy costs for operating an MTJ, and how such cost could be decreased. The work in this project relies on nanofabrication, electronic magneto-transport measurements, and surface imaging. The ongoing plan is to compare the variations in surface features and the tunneling magneto-resistance.

I. INTRODUCTION

In the past, the strive to make complex electronic components smaller and smaller has proven itself essential to increasing the computational power of computers.[1] With modern transistors having some features (channel width, oxide thickness) approaching a few nanometers in size, the development of other nanodevices is quick to follow. One such family of devices are various proposed spintronic devices, such as spin diodes, spin transistors, etc. Spintronics devices might utilize spin or the combination of spin and charge in their operation.[2] Spintronics has been a growing area of research and development since the late '90s, as condensed matter physicists have had an increased interest in the transport properties of specific materials. While spintronics and solid-state physics are very general subjects and terms, there is a large focus and study on various junctions of materials and their transport and electronic properties. From superconducting junctions like Josephson junctions, or to the well-known P-N junction diode, there are many ways to arrange and manipulate materials to measure unique properties and see various effects.

The need for efficient, reliable, and small magnetic devices has been apparent since the advent of digital computers. Many storage media for data like floppy disks or cassette tapes rely on the polarization of magnetic materials to encode data on these surfaces. While technologies like those might seem to be overshadowed by modern advances in solid-state technology, the need for magnetic data storage and control is far from the past. Hard drives use positive and negative magnetization on disks to store data, and to this day proves to be one of the cheapest ways of storing data in large quantities.[3] The heads that read data from disks in hard drives work on the same principles as magnetic tunnel junctions, with further technologies being developed as well.

One such unique arrangement is the aforementioned magnetic tunnel junction or MTJ for short. MTJs are most simply 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 junction can range in material type, size, shape, as well as many other parameters, but must contain those three elements.

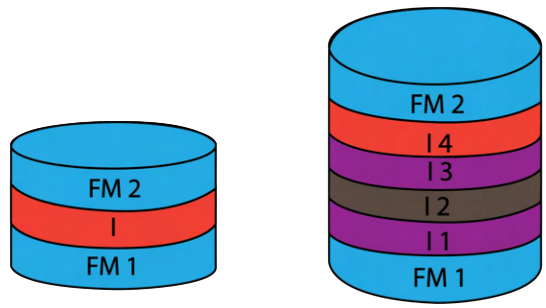

FIG. 1. An example diagram of magnetic tunnel junctions, which can have as few as three layers (left) or consist of multiple layers (right) Ferromagnetic layers like Fe or Co are labeled FM, with various oxide or tunneling layers labeled I

Magnetic tunnel junctions rely on a few key principles from condensed matter physics for their application and operation. One key principle that governs their use is spin dependant tunneling, a phenomenon that has electrons tunneling through the insulating layer of the MTJ, but as a function of the electron's spin. Current passes through with the flow of electrons, but this is highly dependent on the relative orientation of the magnetization of the ferromagnetic layers.[4] If the magnetizations of the ferromagnets are opposite in direction, then the resistance of the junction is very high, and electrons will not flow, while the opposite is true if the magnetizations are aligned. This property of the junction is called tunneling magneto-resistance (TMR).

While these junctions are nanodevices, and relatively small, optimizing these junctions for efficiency and power consumption proves to be extremely important. For an individual junction, power consumption might be on the order of negligible energy loss, but at large scales, these power losses add up and prove to be a subject of concern. The aforementioned design parameters like relative size, shape, and material prove very influential when it comes to the efficiency of the junctions. One such design parameter that is aimed to be explored is the surface properties of both the ferromagnetic and insulating layers.

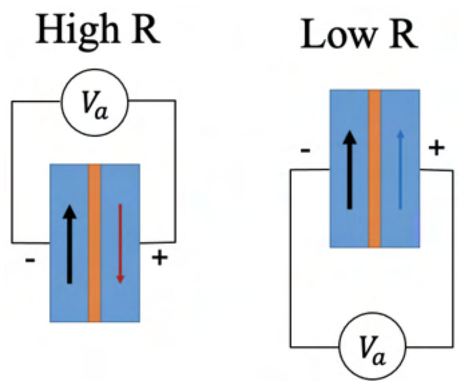

FIG. 2. Resistance of MTJ with the changing orientation of magnetization

Most simply, these layers are designed to be "smooth," with flat surfaces at the junction of each material type. Due to magnetic anisotropy, the phenomenon that magnetic properties of materials are directionally dependent relies on the design and "stepping" of the surfaces.[5] Since the stepping and surface properties of these materials affect the magnetic properties, it is key to explore their effect on the efficiency of these junctions.

Another important property of MTJs is their magnetization as a function of the applied magnetic field. This relationship is hysteretic, meaning that while changing the value for the magnetic field, the corresponding magnetization depends on the previous state, having "memory." This forms a loop while sweeping magnetic fields, the shape of which is dependent on the material type and construction of the junction. It is imperative to understand this hysteresis as it affects the power consumption of the junction.

As a result of all of these phenomena, it is quite possible that spin-based electronics, like MTJs are the energy-efficient solution to issues with downscaling of traditional electronic devices.[6] In order to explore these possibilities, the effect that various surface properties and features have on the tunneling magneto-resistance must be understood.

II. BACKGROUND

A. Magnetic Anisotropy

Exploring the surface properties and geometries of magnetic materials is nothing new, and has been investigated since the mid to late 1990's.[7,8] The aforementioned stepping refers to the surface of the material appearing like a washboard, with atoms removed or added to the surface to create ramped shapes,[9] as seen in Figure 3. These steps and vacant atom sites can be created through a myriad of techniques, both chemical and lithographic, like molecular-beam epitaxy, sputtering, and dry and chemical etching, which are very important in designing precise MTJs.

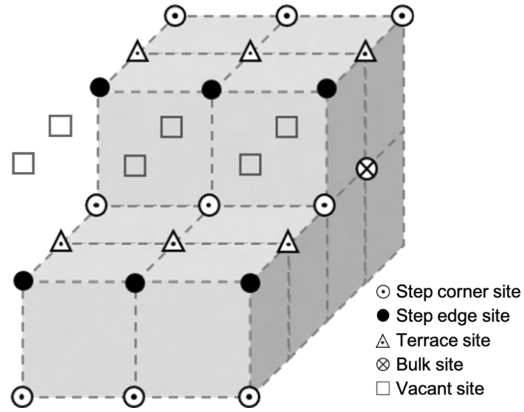

FIG. 3. Diagram of stepped surface and vacant sites, and the definitions of various types of atoms on stepped surfaces

Creating precise steps is important because in order to fully control the magnetic properties of the junction, full confidence in the consistency and shape of the steps is needed. Atoms on the edge or corner are pivotal to controlling the magnetic anisotropy of the material, as with a smooth and consistent surface, all atoms share the same neighboring atoms, making the contributions to bulk properties uniform. However, for atoms on the edges and corners of surfaces, vacancies of neighboring atoms allow for changes in these contributions that affect the influence of magnetism.[10,11]

As seen in Figure 3, there are vacant, bulk, corner, edge, and terrace sites. Vacant sites are where atoms would likely be in a normal crystal structure, but have been removed to create the other types of sites. Bulk sites have all neighbors and next-nearest neighbors as the unaltered crystal structure, and have the same magnetic properties as the bulk unaltered material would have. The terrace sites sit on a flat plane, or terrace, missing atoms above the flat surface. Corner sites have neighboring atoms on six of their eight corners while the edge sites only have neighboring atoms in two of the eight. The anisotropic energy of the film can be given by the equation

$$E_{film} = E_{bulk} - 2 \cdot \frac{E_{terrace}}{t} - 2 \cdot \frac{(E_{edge} + E_{corner})}{td} \quad (1)$$

showing how each type of site contributes to the overall properties of the material.[5] t is the thickness of the film and d is the width of the terrace. Since there are no atoms in the vacant sites, they do not contribute to the energy but are helpful to visualize the difference in the types of sites.

The energy required to operate these junctions is also directly proportional to the product of the magnetization and the applied magnetic field. It can be seen in Figure 4,[9] that this is also equal to the area of the hysteresis loop created by the junction. Controlling the surface features and stepping changes the shape of the hysteresis loop, and in turn, changes the energy needed to operate a magnetic tunnel junction. Note that the axis scaling on the images is different but the change in surface properties changes the shape of the loop in junctions of the same material.

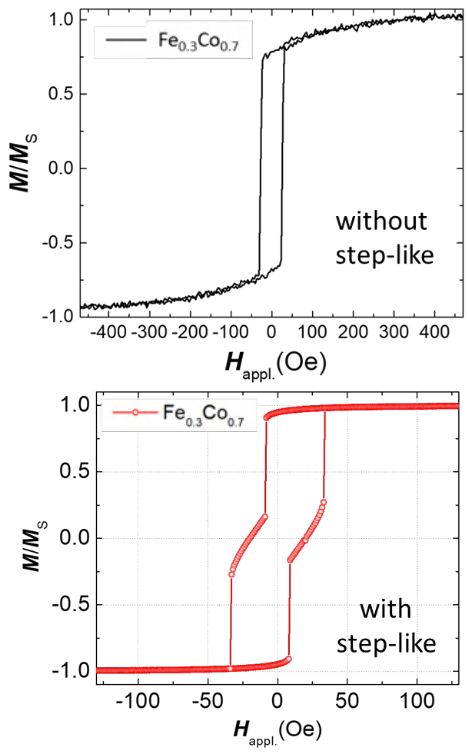

FIG. 4. Hysteresis loops for magnetic tunnel junctions as grown with approximately flat surfaces (top) and stepped surfaces (bottom)

B. Controlling the Operation of MTJs

Another key piece of physics needed to the control and operation of MTJs is the presence of Spin Transfer Torque (STT) due to spin-orbit coupling (SOC). 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, means the flowing electrons have spins aligned in a single direction, which can pass some spin angular momentum to the magnetization of the ferromagnetic resulting in a change in the magnetization.[15] Using the spin-polarized current to alter the magnetization in turn changes the resistance across the junction. In order to create a spin-polarized current, magnetic materials or external magnetic fields are typically needed. Another method of changing the magnetization is Spin Orbit Torque (SOT). SOT also allows for the manipulation of the magnetization, much like STT, but shows the possibility of controlling the resistance of the junction with no need for external magnetic fields.[16]

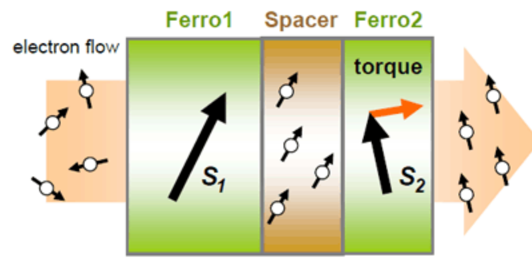

FIG. 5. Operating MTJs using Spin Transfer Torque

This works on the aforementioned principle of Spin Orbit Coupling. SOC is the result of the spin and the orbital motion of the electron interacting to cause a small fundamental link between the two. As a result of this, coupled with the Hall effect, gives rise to the Spin hall effect, resulting in the accumulation of opposite spins at the opposing sides of a material. As seen in Figure 5,[17] the spin-polarized current passes through the second ferromagnetic layer which changes the magnetic moment and applies a magnetic torque. This magnetic torque can be described by

$$\frac{d\vec{M}}{dt} \propto -\vec{M} \times (-\vec{M} \times -\vec{H}), \tag{2}$$

where $\vec{M}$ is the magnetization of the layer and $\vec{H}$ is the external magnetic field. This is used to generate and transport electrons of various spins, which can in turn manipulate and control the magnetization of the junctions. While external magnetic fields can be used to change the magnetizations of the junctions, that method is limited in its ability to scale with the junctions, and STT & SOT have shown to be reliable and scalable methods of controlling MTJs.

III. METHODOLOGY

A. Creating Arrays of MTJs

Arrays of MTJ devices are made on wafers using various nanofabrication techniques. On each wafer, individual junctions are designed to the same parameters like size, stepping, and material etc. Films of the ferromagnetic material are used as a base, while substrates are deposited on top to be etched,[12] after which, another ferromagnetic film is layered atop, completing the trilayer junction. As previously mentioned, there are many techniques such as molecular beam epitaxy or MBE, which works to create such stepping, but have certain obstacles such as requiring an ultra high vacuum in order to work properly.[13]

To produce the magnetic tunnel junctions explored in this project, sputtering was used. In general, sputtering is a technique that uses ions to eject material from a target which then is deposited onto the substrate below.[14] A mask is used to guide where the ejected material lands in the substrate and can be moved around in order to create a desired geometry or pattern. The mask is typically made from glass that has been precisely prepared and then coated in a dark-colored metal layer. From Figure 6, it can be seen that the mask allows the substrate to be removed in the areas under the holes, while the areas blocked by the mask remain unchanged. These optical masks are used for etching larger features, but on smaller scales, computers guide the ions onto the surface directly without the need for the masks.

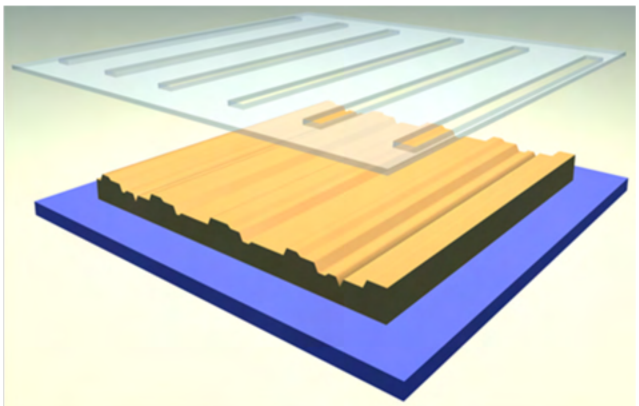

FIG. 6. Schematic of the process for creating step-like surface to nanoengineer the surface magnetic anisotropy

After the lithography of the layers is complete, a final ferromagnetic film is layered atop, such as FeCo, an ferromagnetic alloy, completing the junction seen in Figure 7. Like previously discussed, a stepped surface contributes to change in the magnetic anisotropy of the material, which allows a change in the resistance of the junction in cases in which the magnetizations of the two ferromagnetic layers are parallel, and anti-parallel (opposite from each other). The TMR can be written as a result between these two resistances with

$$\mathrm{TMR} = \frac{R_{AP} - R_P}{R_P}, \tag{3}$$

where R_{AP} is the resistance in the anti-parallel state and R_P is the resistance in the parallel state. This resistance can be measured with traditional techniques, such as applying a voltage and measuring the current across the junction. With larger values for TMR, larger values of resistance are able to be controlled by manipulating the magnetizations of the layers.

The junctions explored in this project are all trilayer junctions. One ferromagnetic layer was iron and the other was an iron cobalt alloy. The insulating layer for these junctions is made of magnesium oxide. These layers are abreviated and written as $\mathrm{Fe|MgO|Fe_{0.3}Co_{0.7}}$.

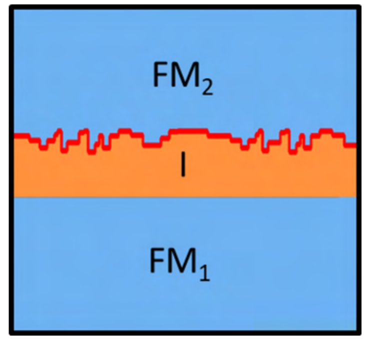

FIG. 7. Cross section of an MTJ with a stepped insulating layer

B. Imaging The Devices

Once junctions have been fabricated, the devices must are imaged in order to evaluate the effectiveness of the lithographic methods. Traditional optical imaging techniques reach their limits at the scale of manufactured MTJs, so other methods must be employed. Scanning Electron Microscope (SEM) imaging allows clear and precise images on scales that optical microscopes cannot reach. SEM imaging uses a focused beam of electrons to reveal the surface topology of the junctions. These images allow us to measure the size of the junctions as well as their shape compared to the design specifications. The microscope used was a JEOL JSM-6360LV.

While SEM images allow us to see the arrays of junctions, they do not show the full picture in terms of evaluating the surfaces of the junctions, and how the etched steps appear on the junctions. To see these surface properties, Atomic Force Microscope (AFM) imaging must be used, as the probe tip contacts the surface of the junctions and shows the entire picture and scale of the nanodevices. The AFM used is a Bruker Dimension Icon, using the NanoScope controller and software. AFM imaging has been used in the past to explore the surfaces of these nanodevices and allows a high level of detail and precision in the final image.[18] Atomic Force Microscopy allows the evaluation of the features and steps that were designed, for and evaluating the effectiveness of the sputtering used to shape the junctions.

With the NanoScope imaging software, the scans are able to be processed and cleaned to remove noise and variations that may have occurred during the measurements. The NanoScope software gives both 2D and 3D scans of the surfaces of the devices and includes various analysis tools that allow careful and precise evaluation of the data.

Looking at Figure 10, it can be seen that looking at the surface in a 3D scan shows many features and intentional design aspects of the junctions, which will be explored later. On the image, a change in height corresponds to different colors, as the surface varies in height by tens of nanometers across the junction. Looking at

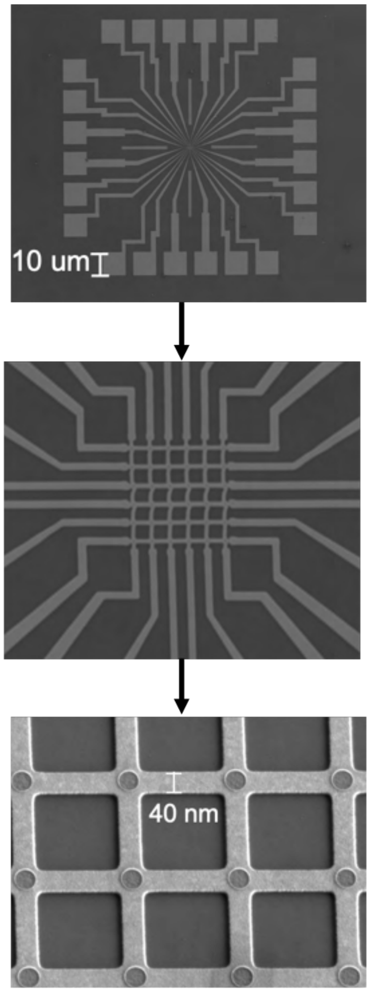

FIG. 8. SEM images showing full arrays of devices with electrical leads (top) zooming in to show individual junctions at the intersection of wires (bottom)

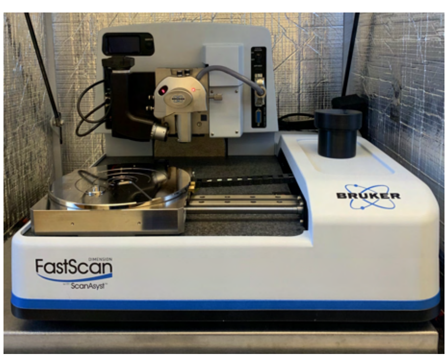

FIG. 9. Sample stage of AFM used to image junctions

these images, the surface features can be related to the transport data, with surfaces of greater slopes and with more steps having larger values for tunneling magnetoresistance.

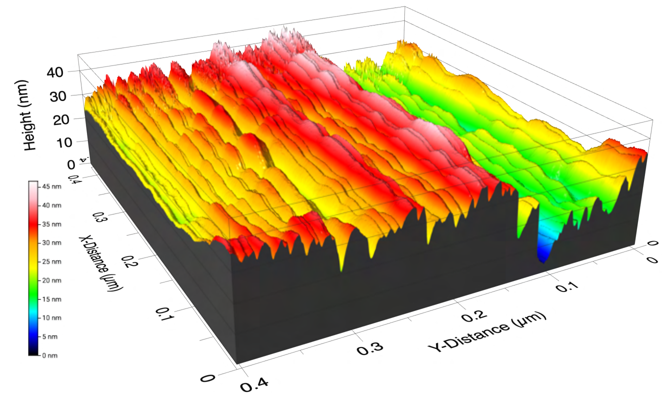

FIG. 10. Typical AFM image of the surface of a junction

C. Measuring Transport Properties

Measuring the resistances of junctions to find the TMR for the devices is no different than finding the resistance for a normal electrical device. However, since these devices can be operated on a variety of magnetic fields or with various bias voltages, special equipment is needed to measure them. The device used to characterize the MTJs explored in this project is the Keithley 4200 SCS, which is designed to work with semiconductor devices, but is not limited to use with them. As seen in Figure 11,[9]measuring the TMR as both a function of bias voltage and external field provides useful insight.

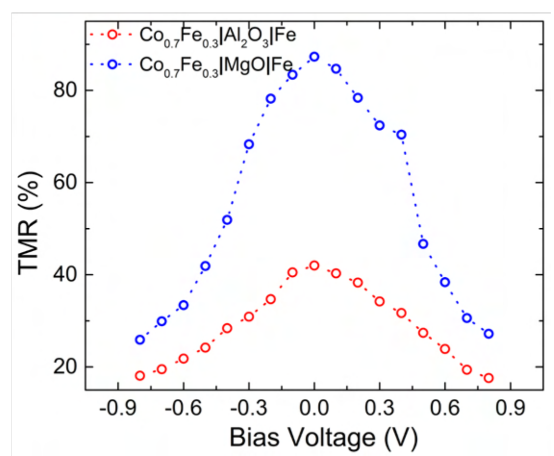

FIG. 11. Typical data for a junction plotting TMR vs. Bias Voltage

IV. RESULTS

A. AFM Images

After imaging a series of junctions using AFM imaging, and analyzing the data, surface shapes, features, and

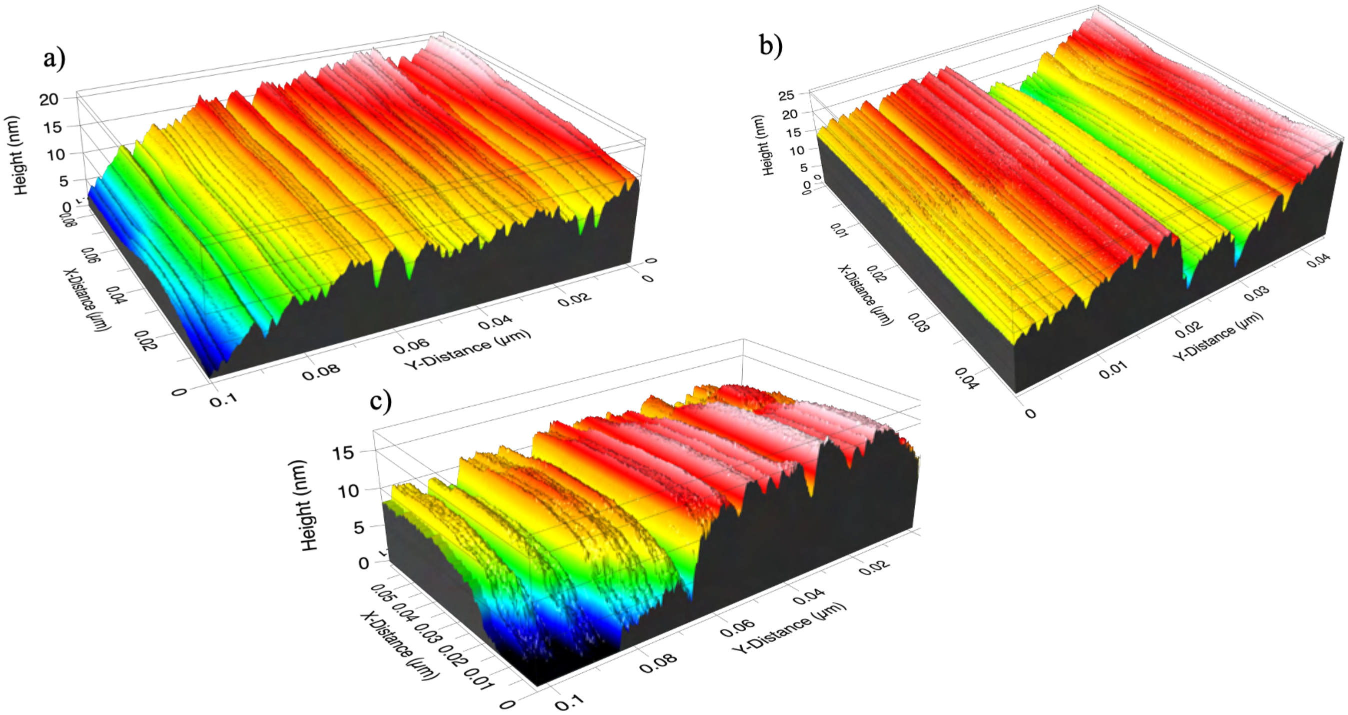

FIG. 12. AFM images of three different devices a) The device surface has a high slope and step density b)The device surface has a moderate slope and step density c) The device surface has the lowest slope and step density

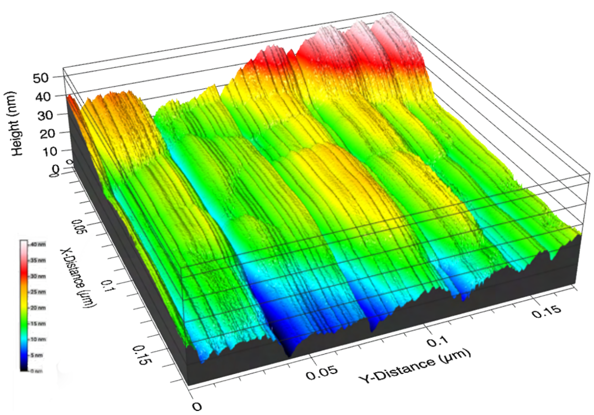

FIG. 13. Raw AFM scan of the surface of a junction showing steps

the consistency of the manufacturing processes can begin to be evaluated. Figure 13 shows a raw scan from the surface of a device. It can be seen that across the device, there are intentional stepping done while manufacturing. However, the red area at the top of the image is a large area much higher than the rest of the surface, caused by inconsistencies in the sputtering done to grow the surface features. This large area both weakens the performance of the junction and makes it difficult to explore the image further. Due to this, many of the images are processed and cropped to focus on the areas with the clearest features.

Each junction scanned is designed to have different levels of stepping and surface shapes, which often repeat periodically across the surface of a single device. Important features to note are the slope of the surface, as well as the concentration and depth of the sputtered steps.

B. Comparing with Transport Properties

Data were taken for the transport properties of the junctions imaged and were inherited for the use of this project. The transport data inherited were taken at a constant magnetic field of 0.03 T. Looking at Figure 14, it is seen that data for three separate devices are plotted. While all the data follows the same shape, the peaks of each curve drastically differ for the junctions. Looking at the images from Figure 12, the shapes of the surfaces and the features are related to the TMR data.

The device with the highest sloped surface and greatest step concentration, labeled a) in Figure 12, corresponds to the orange curve in Figure 14, the device with the highest TMR. For the following two devices b) and c), each has a shallower slope and fewer steps and produced the red and blue curves respectively.

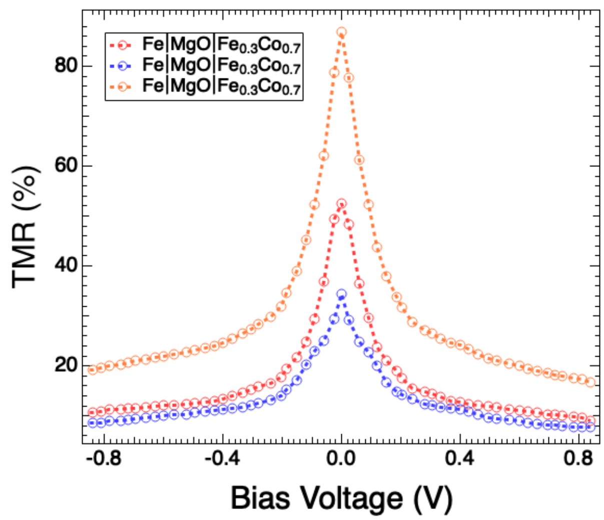

FIG. 14. Plot of TMR vs. Voltage for the three samples from Figure 12

V. CONCLUSIONS

Using various imaging techniques, we have observed intentionally stepped and sloped surfaces on MTJ nanodevices. The images support the transport and TMR data collected it is seen that with heightened stepping and slopes, higher values of TMR are attained. With the heightened tunneling magneto-resistance, the junctions can be operated more efficiently. We have observed a relationship between the manufactured steps and the tunneling performance of the junctions. The energy needed to operate a magnetic tunnel junction is related to the tunneling performance. We can say that manipulating the magnetic anisotropy of the surfaces by introducing stepped and sloped features has a positive impact on the energy costs for the junctions.

VI. FUTURE WORK

While magnetic tunnel junctions are still relevant devices in spintronics, there is still much more to understand about these nanodevices. Understanding the energy efficiency of these as a function of many parameters is still ongoing. While exploring these, understanding how small these junctions can get while still maintaining the ability to manipulate magnetic anisotropy is something to be explored further. Scaling down the junction requires more complex models to understand effects at smaller scales. When it comes to manufacturing nanodevices, there are also many aspects that must be studied further. One question is how effective methods like sputtering and ion-etching can be when producing MTJs with thin oxide layers. Finding potential applications in magnetic memory devices fuels the desire to understand both the efficiency of these junctions and how they best can be used in computing applications.

VII. ACKNOWLEDGEMENTS

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