Project Report for Spintronics 2019-2020
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Spintronics Domain Wall Logic: The Y-Gate

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Abstract
In this report, I'm going to investigate a possible **spintronics logic-device** based on **magnetic domain wall transmission**. The analysis is entirely performed on **OOMMF**, a micro-magnetic simulation environment which solve the LLG equation, with a finite element algorithm.
The **micro-magnetic device** under discussion, that I have renamed the**Y-Gate**, is a well-studied configuration, therefore a comparison with experimental results is possible.
The basic concept behind this domain wall logic is simple: by **injecting** either one (or two) **domain wall(s)** (DWs) into the junction **input(s)**, it is possible to **achieve** a specific boolean operation in **output**, triggered by a proper **static magnetic field**. **The local inversion of magnetization**, due to a domain wall, is identified as the **logic-bit 1**, the **absence** of inversion is the **logic-bit 0**. By changing internal parameter of the structure, e.g. local exchange bias, is possible to drive the structure behavior towards an AND or an OR gate. The path followed in this report is here briefly summarized:

- **First**, I'm going to review the basic idea behind domain wall devices, discussing the limits and the potentiality. After that the work general **methodology and project goal** will be presented.
- **Second**, the methodology will be applied on different structures, with the aim of optimizing the behavior. In parallel the **simulation results** will be presented and discussed.
- **Third**, the project outcome will be recollected and compared with few experimental results. The **simulation limits and possible upgrades** will be taken under exam as well.

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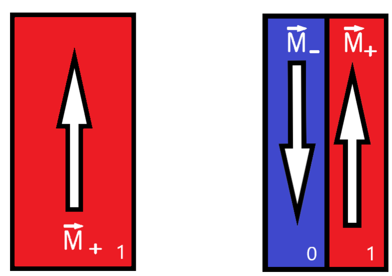

Figure 1. Example of domain wall in a ferromagnetic bar. One can conventionally associate the red magnetization as 1, and the blue magnetization as 0.

1. Introduction

1.1 Domain walls and spintronics devices review

Our modern era is based, and, mostly, relies on microelectronic devices. These exploit the control of electron current to store electric charge, the lack or the presence of the latter fixes the convention on digital signal and has opened the world to binary information.
In the last decades many researchers have discussed the possibility to exploit different quantum proprieties of matter to be associated with the binary representation, spin is, for sure, one of the most attractive.
Thus, spintronics is the field of study that aims to use the spin to store and manipulate the digital information.
Spintronics is already present in many electronic devices. Indeed, every time one wants to store for long time data magnetic memories are used. The idea of substituting other elec-

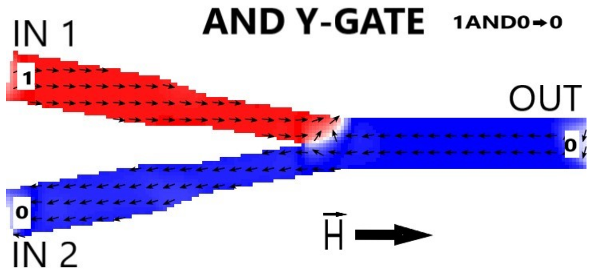

Figure 2. The Y-Gate, final configuration of the simulation. $IN1 = 1$ and $IN2 = 0$

tronic elements with spintronics based devices is extremely interesting.
Within magnetic-based device, one possible direction is to realize domain wall logic [2]. A domain wall is an interface between regions of oppositely aligned magnetization. They are a consequence of an energetic balance between two different material behavior. On one hand, the ferromagnetic exchange interaction between dipoles tend to maximize the magnetization, on the other hand there is the magneto-static energy cost, which is higher for highly magnetized material. As a result one have the formation of domain walls that divide the magnetization in two (or more) different magnetization orientations, called magnetic domains, see **Figure 1**. A generic introduction on the subject can be found in chapter 6.7 of [3].
If we are able to exploit shape anisotropy of magnetic films, like $Ni_{80}Fe_{20}$ permalloy, then we can create devices that holds at equilibrium two direction of magnetization [1], that we can associated to a bit 0 and bit 1.
Moreover, it is not hard to imagine that under a certain magnetostatic H-field this magnetic walls can propagate, propagating, therefore, also the associated binary information.
One will have and AND behavior when a structure, like **Figure 2**, will propagate a domain wall to the output junction if and only if domain walls are injected in both input junctions. On the contrary, one will have an OR behavior when it is needed at least one injected domain wall to achieve the domain propagation to the output.
The advantages of this solution are clear:

- Very little heating caused by data switching, compared with current based device.
- Possibility to implement three-dimensional domain wall logic structure [2].

However, many disadvantages make this solution less convenient. Some of these limitations naturally arise from the simulations. Therefore, to be consistent, this discussion is postponed in the last section of the report.

1.2 Methodology for the design of the Y-Gate

Before arriving at the configuration of **Figure 2**, a long path has been taken. **Figure 2**, is however useful to fix the conventions adopted in the report for the working channels.

The project request was, in origin, to characterize the behavior of a given structure, **Figure 5**, and to find the best external parameters that make the structure working as an AND or OR gate. It was not known, a priori, whether that structure was capable of performing that aimed task. Therefore a methodology to evaluate generic structure was needed. This iterative methodology allows not only to characterize the structure behavior but also to pinpoint limitations and, eventually, redesign the whole structure.

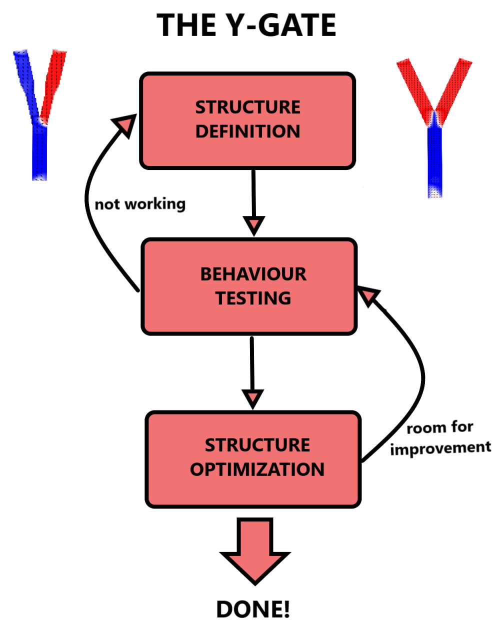

Figure 3. Sketch of the design methodology followed in the report.

In detail,
A suitable material is chosen, $Ni_{80}Fe_{20}$, and its parameters are imported in the micro-magnetic simulation environment.
Structure definition:
The structure is geometrically defined, the regions of interest are identified with different colors, in order to be associated in OOMMF with different initial magnetizations. Then, the bitmap is imported in the simulation environment.

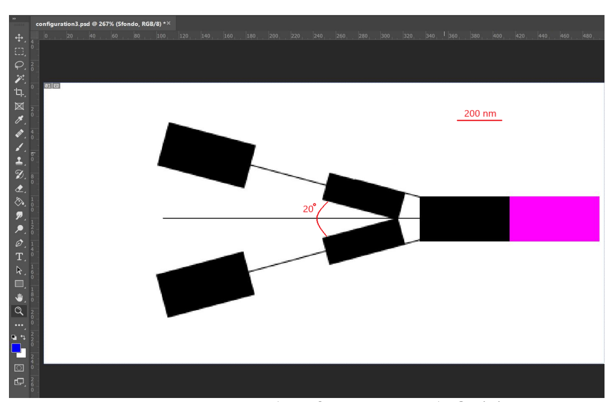

Figure 4. Example of structure definition

Behaviour testing:
The structure is tested in OOMMF according to some specified guidelines that depends on the kind of logic gate we want to test.
E.g. in the **AND** case, by varying the static H-field, always applied from left to right, the testing step followed are:

- find the H_{min} at which we achieve the AND behavior by the injection of domain $IN1 = 1$ $IN2 = 1$ channel.

- find H_{max1} at which we fail in holding the aimed behavior, i.e. a domain wall injected only in $IN1 = 1$ $IN2 = 0$ result in a complete magnetization of the whole structure.

- find H_{max2}, $IN1 = 0$ $IN2 = 1$.

Clearly everything works properly if $H_{min} < min(H_{max1}, H_{max2})$, if this condition is not satisfied the structure needs to be re-designed.

Structure optimization:
The structure is optimized accordingly to some optimization parameter like: structure size, H-field magnitude that enables the structure functionality, $\Delta H = min(H_{max1}, H_{max2}) - H_{min}$ that one can call for clear reason **structure stability**.
ΔH is a key parameter that fixes the range of tolerance we have in selecting the static field. A small ΔH implies that if we fix a wrong H-field for the logic devices we can have, more likely, wrong behavior.

1.3 Design goal and project outcome

As in any self-consistent work we should underline the purpose of the project. The simplistic answer: *for academic purposes* might be quite convincing.
But, *what is beyond that?*
To find potentially better solution of well known problems is a nice mental effort. Moreover, to rethink the current electronics, by basing everything on different physical mechanism, can lead to innovative solution that can eventually brings to a game changer technology.

So the design goal could be resumed in *"to discuss and characterize via micro-magnetic simulations the behavior of a structure that was thought to be a potential alternative to electronic-based logic device"*. Therefore, the project outcome are evaluated considering this initial scope.

In the project three structures have been evaluated.
The first structure considered was the one initially proposed in the project statement, **Figure 5**. It has been demonstrated that this structure cannot sustain and AND configuration. Indeed, following the methodology, the condition it turns out that $H_{min} > min(H_{max1}, H_{max2})$, i.e. we have a complete magnetization of the whole structure before the domain wall transmission[1]. This can be justified by saying that with an angle of 45^o between the two junctions, we achieve stable configuration that holds, even at high applied fields, 160 Oe.

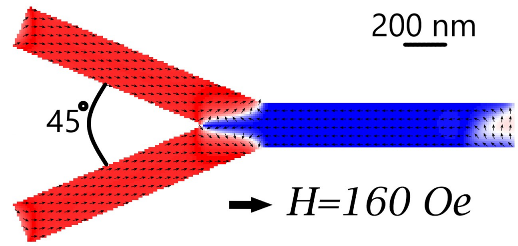

Figure 5. First tested structure, not working configuration. The structure is stacked in an equilibrium configuration that do not allows domain propagation.

In **the second structure** considered, I have decided to decrease the angle to 30^o. In this way, thanks to the film shape-anisotropy, the two junctions have a magnetization more oriented in the H-field direction increasing the energy gain of a parallel orientation. Therefore, I expected that a domain wall would propagate more easily. This new configuration worked finely, as an AND gate, for a field of 86 Oe.
However, the stability factor $\Delta H = min(H_{max1}, H_{max2}) - H_{min}$ was too low for our purpose, $\Delta H = 1$ Oe. Therefore, a new configuration was needed.
In **the third** and last **configuration** considered, I was inspired by the design suggested in [1] and [2].

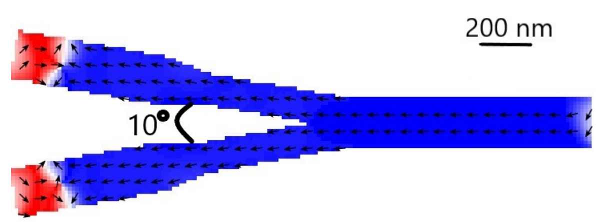

Figure 6. Final structure configuration, the Y-Gate

The [1] reported structure is not optimized from a dimension point of view, it is, indeed, roughly 5 μm long, for sure not competitive with the state of the art logic gate. For that reason, in my simulated design, I have tried to half the dimensions, the result is a 2.5 μm x 0.8 μm structure that can perform both AND and OR functionality.
The AND function was achieved at $H = 101$ Oe $\Delta H = 5$ Oe, this value is still not optimal for stability so, for practical purposes further optimization should be implemented.
The OR function, instead, was achieved by keeping[2] the external field at $H = 101$ Oe and by applying in the cross region, red zone in **Figure 7**, an exchange bias of $H_{exb} = 6$ Oe, among

[1] A video showing the reported behavior is available at https://youtu.be/jbwxlmalQJo

[2] If we want to realize a device, it might be reasonable to work with the same field for both the behavior

the same direction of the H-field. In the next section I will discuss in technical details the results with this final structure, at the end of the same section I will evaluate the propagation velocity of the domain wall, comparing the simulation results with the experimental one.

2. Simulation results discussion

Structure and mesh

The structure has been realized in Photoshop, to manage with single pixel accuracy the whole object.

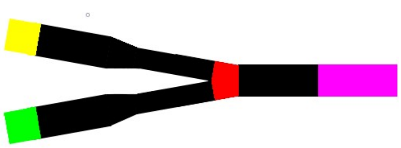

Figure 7. Imported image, 2D ”top view”

The structure is a 3D object , where **Figure 5** is the in-plane top view with an out of plane extension of 5 nm. The regions of interest have been signed with different colors to allow localized magnetization control. In particular this has been done with the two input wire, yellow and green, the middle region for the implementation of the OR functionality, in red, and the output wire for testing purpose, in purple. At this point the mesh dimension was needed to be specified. Indeed, in OOMMF it is extremely relevant to define the size of the cell that is going to be used in the finite element algorithm, bigger size means less precise but quicker calculation. In the first place a **10x10x5** nm cell was selected. Evaluating the dynamic with TimeDriver[3] everything worked fine, even for the structure of Figure 3. However, evaluating the permalloy exchange length, as well as the domain wall size, it turns out that the chosen cell mesh was not correct for our simulated object.
Given the exchange constant $A = 10e-11\ \frac{J}{m}$ and the saturation magnetization $Ms = 8.4e5\ \frac{A}{m^2}$.

$$\lambda_{ex} = \sqrt{\frac{2A}{\mu_0 Ms^2}} \tag{1}$$

$$\lambda_{ex} = 4.748 \quad nm \tag{2}$$

Therefore, to be realistic, I have scaled down the dimension to **5x5x5** nm, this leads to the discard of the first structure and started the journey toward the final structure, **Figure 6**. This clearly have significantly slowed down the simulation, thus, in order to evaluate the equilibrium configuration only CGEvolve, MinDriver[4], was used for most of the time[5].

2.1 AND behavior testing

For the AND gate the methodology has been already explained in the first section, therefore after many tests[6], it has been obtained a $\Delta H = 5$ Oe with a working field at $H = 101$ Oe. This is a quiete reasonable field comparing its value with the literature. In [2] [4] a similar structure has been evaluated, they have achieved $H = 40Oe$ with around $\Delta H = 15Oe$, i.e. their structure output switches at 65 Oe with just one input present. The main draw back of [1] structure is that it is more than 5 times bigger than our Y-gate.

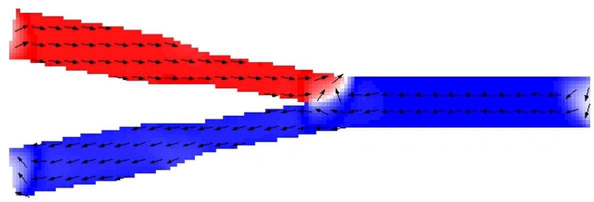

Figure 8. AND gate at $H = 101$ Oe, stable condition.
$IN1 = 1\ IN2 = 0\ OUT = 0$

2.2 OR behavior testing

With a similar approach the OR configuration has been evaluated. We expect, that the presence of an exchange bias directed in the same direction of the magnetic field, will play in favor of the domain wall propagation. Therefore, a bias will act on singly magnetized input, as in **Figure 7**, as if also the other junction was inverted, this is, indeed, an OR behavior. For obvious reason[7] the structure is supposed to work at the same field of the AND configuration. Hence, in order to win the stable state of **Figure 7**, an exchange bias has been applied in the red zone of **Figure 7**.
The method applied is the following:

- Fix the size of the red zone.
- Testing $IN1 = 1/0\ IN2 = 0/1$ with external field $H = 101$ Oe, find the $H_{min1exb}$ that enables the OR.
- Testing $IN2 = 1\ IN2 = 1$ with external field $H = 101$ Oe, find the $H_{min2exb}$ that enables the OR.

The working condition[8] is $H = 101$ Oe and $max(H_{min1exb}, H_{min2exb})$ fixing a certain exchange bias zone. Running the simulations

[3] The OOMMF solver that evaluate the dynamics followed to reach an equilibrium configuration.

[4] The OOMMF solver that evaluate in a quicker way the minimum energy configuration for the structure, without telling any information on the real dynamic.

[5] At the end of each test also TimeDriver was used to check whether the results were consistent

[6] A video showing the reported AND behavior is available at https://www.youtube.com/watch?v=VdXqNY17ex4

[7] If we imagine to use this Y-Gate for computation we want to control multiple logic gates with one precise H-field

[8] Video of the OR behavior are also availablehttps://www.youtube.com/watch?v=qLvOpmqlJLI

an OR is achieved with an exchange bias of $H_{exb} = 6$ Oe. At this point, I have studied the $max(H_{min1exb}, H_{min2exb})$ by changing the size of the red zone, i.e. expanding D, **Figure 9**. In all the measurements from $D = 0$ to $D = 80$ nm, no appreciable change in the exchange bias, needed to achieve OR behavior, can be detected, this is justified in the next lines. To conclude we can infer:

- The H_{exb}, needed to pass from an AND to an OR configuration, is almost equal to the structure stability ΔH, this is agreement with the initial expectation.
- The almost flatness of the function (H_{exb}, D) can be justified by saying that the exchange bias has a major role only in the neighborhood of the junctions domain wall. In other word, if we apply an exchange bias extended over a wide region, the sub-region that will help the domain wall propagation will be a very limited one near the domain wall.

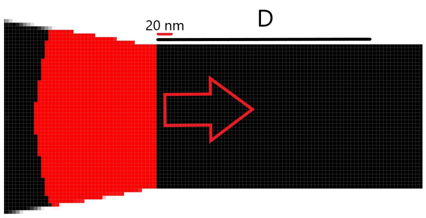

Figure 9. Details of Figure 5, D=0 configuration. The exchange bias is applied in the same direction of the external H-field.

2.3 Domain wall velocity

Another interesting study, that has been done on the structure, was to find the domain wall propagation velocity. This information is particularly relevant if we want to have an estimation of the computational velocity of this device. For a standard computer a good estimation for the operation velocity is the computer clock, in the GHz (10^9 Hz) order. It means that if we ask to compute an AND operation the time required to make the calculation can be approximated as 1 ns. For the Y-Gate it has been measured a simulated domain wall velocity of roughly 600 $\frac{m}{s}$, in literature a value of 1000 $\frac{m}{s}$ [2] is reported. It means that to propagate for 2.5 μm, roughly the length of the path, the time taken is approximately 4 ns, roughly of the same order of magnitude of the standard computer. The simulation has been performed by setting a TimeDriver evolver and putting the right damping value. A factor of two is not so irrelevant so it needs to be justified. There could be two major explanation:

1) The bottle neck introduced in **Figure 7**, shrinks more quickly than the one in [2], this introduce anisotropy effects that may slow down the domain wall, this effect are absent when the anisotropy is spatially constant.
2) The value reported in literature is the maximum instantaneous velocity while, in our case we are measuring an average velocity, length of the path divided by the time taken for propagation.

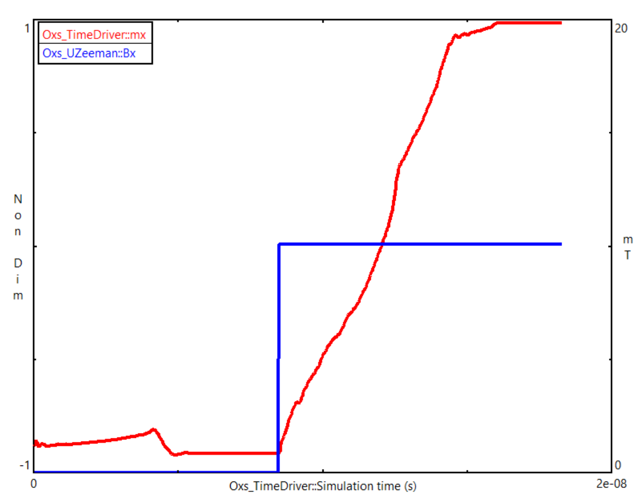

Figure 10. Real dynamic of the Y-Gate in Or configuration, after a relaxation transient $t_{start} = 8.41$ ns a field is applied, then the domain wall arrival to output is estimated around $t_{propagation} = 12.6$ ns.

In **Figure 10**, the dynamic of the OR-gate with $IN1 = 1$ and $IN2 = 0$ has been simulated with $H = 101$ Oe and $H_{exb} = 6$ Oe. The propagation to the output gate of the domain wall corresponds to a 40% of the overall structure magnetization oriented in x-direction. Therefore, in order to estimate the propagation velocity, the interval of time between this event and the turn on of the H-field was measured by pausing the simulation. It was also observed a saturation to 1, 100% magnetization in x, due to the back propagation of the domain wall to the IN2, initially equal to 0. This is a side effect that cannot be avoided within this configuration. It is possible, if necessary, to block this propagation by imposing an additional exchange bias in the left black zones of **Figure 7**.

3. Conclusions

The structure of **Figure 7** is, thus, the final proposed design for the AND-OR logic domain wall based device. This final configuration has been achieved after the discard of two previous structure. The resulting behavior are:

- AND at $H = 101$ Oe with a $\Delta H = 5$ Oe with no H_{exb}.
- OR at $H = 101$ Oe with an $H_{exb} = 6$ Oe and
- 600 $\frac{m}{s}$ of domain wall propagation velocity from IN to OUT.

The behavior achieved is satisfactory, there is, however, big space for improvement. Indeed, the structure shows a very small resilience towards structure defects. In other terms, if we imagine to experimentally realize the structure, then defects on the film spatial dimension may results in an alteration of the $(H, \Delta H, H_{exb})$ proprieties. This alteration behavior shows up many times in the first versions of **Figure 7** design, especially every time a picture with some asymmetry was imported in the OOMMF environment. Therefore, an extra and careful debug was needed to achieve the final version of the **third** structure. The alterations became particularly dangerous when $\Delta H < 0$[9], therefore a configuration with a big ΔH might intuitively be preferred. We have already listed in the introduction the possible benefits of a domain wall logic. At this point, it is simpler to pinpoint also the main problems associated with this kind of spintronics device:

- This device relies on micro-magnetism, therefore there is an intrinsic limits in the scaling down.
- The structure is extremely sensitive to structural defects, therefore an accurate control is mandatory.
- In the Y-Gate configuration, a precise static magnetic field has to be controlled, otherwise unwanted behaviors show up.
  Moreover, even if there is room for structural improvement, a threshold of $\Delta H = 6$ Oe is too small for practical applications.
- To measure the domain wall orientation, techniques like SEMPA (Scanning electron microscopy with polarization analysis), could be used to detect the local orientation, MOKE (Magneto-Optic Kerr-Effect) or also magnetic force microscopy[3].

For sure these techniques are not as comfortable as reading a current, like in modern electronics.
To overcame some of these problems other spintronics solutions have been proposed. An interesting one, that still exploits domain wall propagation, is presented in [4].
In this simulation they do not use magnetization orientation to fix the bit-convention, instead they exploit the chiralirty of magnetic domain wall vortexes.

[9] We loose, indeed, the wanted behavior

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