Tapia: U: Your Story Recorded in a Magnet: Micromagnetic Simulations of Spin-Orbit Torque in Multi-layer Structures

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The aim of this work is to address one of the challenges in computing: the need for novel energy-efficient non-volatile memory devices which have the potential of drastically reducing power consumption by computers, mobile, wearable and embedded electronics. Such memory devices would require zero power to maintain their state and have the ability to start up processes instantaneously. In this micromagnetic simulation study, we demonstrate switching (write-operation) of a magnetic memory unit with Spin-Orbit Torque, not requiring external magnetic field. We propose a novel multi-layer stack which is comprised of a Synthetic Antiferromagnet (SAF) and an antiferromagnetic underlayer (AFM). Efficient field-free magnetization reversal is propelled by the competing exchange fields and spin torques. In addition, we perform an optimization analysis of the parameter space required for deterministic switching. Our simulation results provide a promising approach for developing efficient and stable switching schemes and designing actual devices for future spintronic applications.

1. SOT-MRAM Background

With the explosion of IoT promising global connectivity for a sea of computers, gadgets, sensors and wearables, there is a pressing need for developing energy-efficient hardware to sustain such a broad network of devices operating simultaneously: improving energy efficiency is imperative for the reduction of the carbon footprint, and for the extension of battery lifetime in mobile and wearable devices. Spintronic devices which are based on magnetization, or alignment of electron spins, are much more ‘permanent’ than charge-based storage, which requires continuous refreshing, constantly consuming energy. With its ability to combine good read/write speed, high density and non-volatility, Magnetoresistive Random Access Memory (MRAM) is perhaps the ideal alternative to conventional RAM for applications that must store and quickly retrieve data and processor instructions.

Various physical mechanisms based on the quantum mechanical Spin Orbit Coupling effect have been explored; among them, Spin-Orbit Torque (SOT)[10] shows great promise due to its potential for developing high density memory and logic devices with efficient and reliable storage capabilities. In SOT-MRAM memory structures, namely magnetic tunnel junctions (MTJ, shown in Fig.1a), an in-plane current through a heavy metal layer causes accumulation of spin-polarized electrons at the interface with the adjacent ferromagnetic (FM) layer, inducing a torque on it. This torque provides a way to deterministically manipulate the magnetization of the magnetic storage unit, thus encoding a digital bit. Micromagnetic simulations are crucial for quantifying these dynamic switching processes, which are often spatially non-uniform and are governed by the exchange coupling between magnetic domains (groups of aligned spins).

Achieving widespread usage of SOT-MRAM requires improving its thermal stability, reducing switching current, and increasing write speeds. Another significant deficiency of present SOT-MRAM is the need for an external symmetry-breaking magnetic field, required for deterministic SOT switching[11, 2]. All these issues can potentially be solved by introducing novel intricately designed multi-layer structures. In these systems, interlayer and intra-layer interactions, as well as interfacial effects could provide mechanisms to propel magnetization switching, and greatly reduce energy consumption.

Our multi-layer stack combines two aspects to achieve efficient field-free deterministic switching of the free layer. First, thermal stability and decreased stray fields can be acheived by shifting towards synthetic antiferromagnetic (SAF) free layers[18]. Experimental and theoretical studies have demonstrated that in SAF nanowires [8] and thin films [3] displaying perpendicular magnetic anisotropy (PMA), domain wall motion and SOT switching can be enhanced by antiferromagnetic Ruderman-Kittel-Kasuya-Yosida (RKKY) interaction through a non-magnetic spacer layer. We numerically demonstrate how this interaction can drive the SAF switching process. Second, the field requirement challenge can be solved by designing multi-layer stacks where this in-plane bias field is supplied to the FM by an uncompensated antiferromagnet (AFM) such as IrMn[9, 12] or PtMn [6]. In this study, the bias field B_{EB} is only experienced by one of the FM layers, but the RKKY interaction couples the two FM layers and tends to anti-align them.

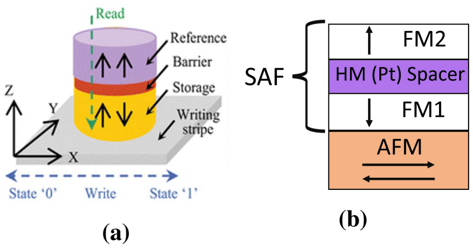

Figure 1: (a)Memory unit - Magnetic Tunnel Junction (MTJ), adopted from [15]; (b)Simulated Structure: antiferromagnetically coupled FM layers separated by Pt heavy metal; antiferromagnet (AFM) supplies exchange bias field to FM1.

2. Structure and Model Setup

The multi-layer structure shown in Fig.1 is simulated, where the two ferromagnets, FM1 and FM2, are separated by a heavy metal (Pt) spacer layer which provides the antiferromagnetic coupling, as well as spin-torque to FM1 and FM2. Since the FMs surround the Pt layer on both sides, Spin-Orbit Torque polarities are expected to be antisymmetric for FM1 and FM2: indeed, a current in the x-direction would produce a spin polarization $\sigma = -\hat{y}$ at the interface with FM1 and vice versa for FM2. Directly below the SAF is the antiferromagnet (AFM) which supplies B_{EB} only to FM1, causing it to cant towards the positive x-axis. Typical observed bias fields for CoFe(Co)/IrMn systems are 40-60mT [6, 9, 16]. Here, the exchange bias coupling strength with the AFM underlayer has been fixed to 0.04 mJ/cm^2, resulting in a bias field $B_{EB} \approx 57$mT pointing along the positive x-axis. The ferromagnetic films FM1 and FM2 were modeled as layers consisting of 256x256x1 cells of size 4x4x0.8nm^3.

GPU-accelerated micromagnetic simulations were performed in the Mumax framework[17] to solve the time-and-space-dependent Landau-Lifshitz-Gilbert equation (Eq. 1) for the magnetization $\vec{m}(\vec{r},t)$. Here, $\beta = \frac{\hbar}{2e}\frac{J_c}{M_{sat}C_z}$, where C_z is the layer thickness, J_c represents the charge current density and σ is the spin polarization vector; θ_i represents the Slonczewski and field-like effective spin-hall efficiency coefficients.

In this study, the original Mumax source code was modified to explicitly include the Spin-Orbit Torque terms (last two terms of Eq. 1). Additionally, inter-layer RKKY and exchange bias fields were added to the effective magnetic field $\vec{B_{\text{eff}}}$, experienced by each FM simulation cell.

$$\begin{aligned}\frac{d\vec{m}}{dt} = &\frac{\gamma}{1+\alpha^2}(-\vec{m}\times\vec{B_{\text{eff}}} - \alpha\vec{m}\times(\vec{m}\times\vec{B_{\text{eff}}}) \\ &- \beta\theta_{SL}\vec{m}\times(\vec{m}\times\vec{\hat{\sigma}}) - \beta\theta_{FL}(\vec{m}\times\vec{\hat{\sigma}})))\end{aligned} \quad (1)$$

In addition, to more accurately represent real ferromagnetic materials, it is common to introduce magnetic 'defects', or regions of reduced anisotropy in micromagnetic models[14]. Micromagnetic simulations often render larger critical switching current than experimentally observed, due to thermal excitations and magnetic grains which cause domain nucleation in real films, thus reducing the switching energy barrier[7]. In our case, randomly scattered regions of 4nm-radius are placed in each of the ferromagnetic layers.

To compensate for the lack of symmetry-breaking magnetic field acting on FM2, we propose a stack design in which the FM2 layer has a weaker magnetic anisotropy. The effective anisotropy field is given by $|B_{anis}| = \frac{2K_{u1}}{\mu_0 M_{\text{sat}}}$ [17] and determines the field required to perform switching from between up-down states. For this reason, the saturation magnetization M_{sat} for FM2 was taken to be larger than that of FM1: $M_{\text{sat}}^{FM1} = 9\times10^5\ \text{A}\,\text{m}^{-1}$, while $M_{\text{sat}}^{FM2} = 9.2\times10^5\ \text{A}\,\text{m}^{-1}$.

3. Magnetization Dynamics

The SAF magnetization switching depends on the interplay between several torque components, including the already mentioned Spin-Orbit Torque, exchange bias and RKKY antiferromagnetic coupling. The model also accounts for intrinsic ferromagnetic propertiess such as magnetic anisotropy, demagnitization, and thermal effects. Furthermore, it is crucial to consider all these fields in the micromagnetic context, where intra-layer spin interactions greatly affect the dynamic properties and switching probabilities. These interactions include the Heisenberg exchange, which tends to align a spin to its neighbors, as well as the Dzyaloshinkskii-Moriya Interaction (DMI). DMI determines the chirality and motion of magnetic domain walls which play a crucial in FM switching processes[13], [8]. The SAF switching dynamics are analyzed further in the micromagnetic context.

The main challenge in the switching of our SAF stack is to achieve deterministic switching of FM2 which does not experience a symmetry-breaking field. As mentioned earlier, FM2 is designed to have a weaker anisotropy, requiring a smaller switching current than FM1. Still, FM2 must be switched entirely by Spin-Orbit Torque and antiferromagnetic coupling to the evolving magnetization of FM1, as well as FM2's intrinsic spin exchange interactions, anisotropy, demagnetization and thermal effects. Of those mentioned mechanisms, only RKKY torque is not 'symmetry invariant' with respect to up-down states of FM2, as it tends to align FM2 opposite to FM1, thus could uniquely determine the final state of FM2. However, the time-dependent RKKY coupling field is not always conducive to deterministic switching of either FM1 or FM2, as will be discussed further.

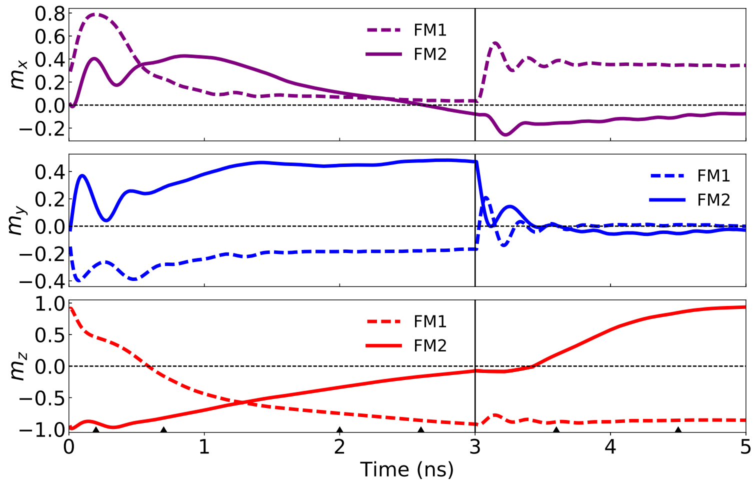

Figure 2: Average magnetization components during the current-driven switching event with $J_x = 4.4 \times 10^8$ A/cm^2. The marked points correspond to the two-dimensional m_z images in Fig.3. The vertical line represents the time at which the current pulse is turned off.

4. Successful Switching Case Study

A successful SAF switching event is first analyzed: Fig.2 shows time evolution of the averaged FM1/FM2 magnetization. The initial state is FM1-up and FM2-down, where the FM1 is slightly canted along the $\hat{x}$ direction due to the in-plane bias field. RKKY interaction strength is taken to be $J_{\mathrm{RKKY}} = -0.014$ J/m^2, DMI parameter is D = 1.2mJ/m^3, in accordance with previous simulation studies [8]. An in-plane current pulse of $J_x = 4.4 \times 10^8$ A/cm^2 is applied for 3ns and then the magnetization is allowed to evolve for an additional 2ns. The vertical dotted lines mark the current pulse removal. It is evident that FM1 switches during the current pulse, and the m_z crossover point occurs at about 1.3ns, while the pulse is still on. FM2 doesn't experience full switching until after the pulse is removed.

Next, the spatial dynamics are analyzed for the same event and the results indicate complex non-uniform switching processes. In Fig 3 (a)-(f), the vertical magnetization component m_z is plotted for both ferromagnetic layers at several time steps to show the spatial switching dynamics. These time points are marked by triangles in Fig.2.

Our results are in agreement with previous analysis of reverse domain wall nucleation, determined by the Slonczewski Spin-Orbit Torque (top-bottom half-plane) and in-plane field (left-right), as demonstrated in Fig. 3 of Baumgartner et al (2017)[1]. In our case, the current polarity is reversed, since FM1 is positioned underneath the Pt layer, thus for the configuration [$m_z > 0$, $J_x > 0$, $B_{EB} > 0$], we expect the reverse domain to be nucleated at the top left corner of the film. This is evident at 0.2ns, Fig.2(a). Investigating the in-plane magnetization components shows that this is a Néel domain wall, consistent with previous SOT reversal studies [1, 8]. However, instead of simple domain motion across the film, the switching process is better described as reverse domain penetration diagonally from left to bottom right, aided by demagnetization and nucleation of reversed 'bubbles'. Analogously, the domain wall formed at the bottom right corner of FM1 at 0.7ns, Fig.3(c), is also consistent with the domain wall analysis[1]. The bottom right edge spins are slightly canted inward ($m_x < 0$ and $m_y > 0$), which reduces the effect of exchange bias field and slows down the switching in that region. However, the strong antiferromagnetic coupling field causes full magnetization reversal of FM1 by 3.6ns, Fig.3(e).

FM2 doesn't experience the same domain wall motion as FM1 due to the absence of an in-plane field; instead, domain nucleation governs its reversal process. After FM1 has mostly switched, the FM2 film experiences a magnetic field of $B_{RKKY} = 17.4$ mT along z-axis. This, scenario is similar to the selective switching observed by Pacheco et al. (2014)[4] in antiferromagnetically coupled PMA bilayers under an external vertical magnetic field. It was claimed that the domain nucleation process is dependent on the sweep rate of the magnetic field: nucleation-driven reversal dominates when dH/dt is high and overcomes domain wall speed, while propagation dominates at lower rates[4]. Similarly, we propose that as soon as FM1 has nearly switched, the rate of change B_{RKKY} acting on FM2 is reduced, thus domain growth dominates the rever-

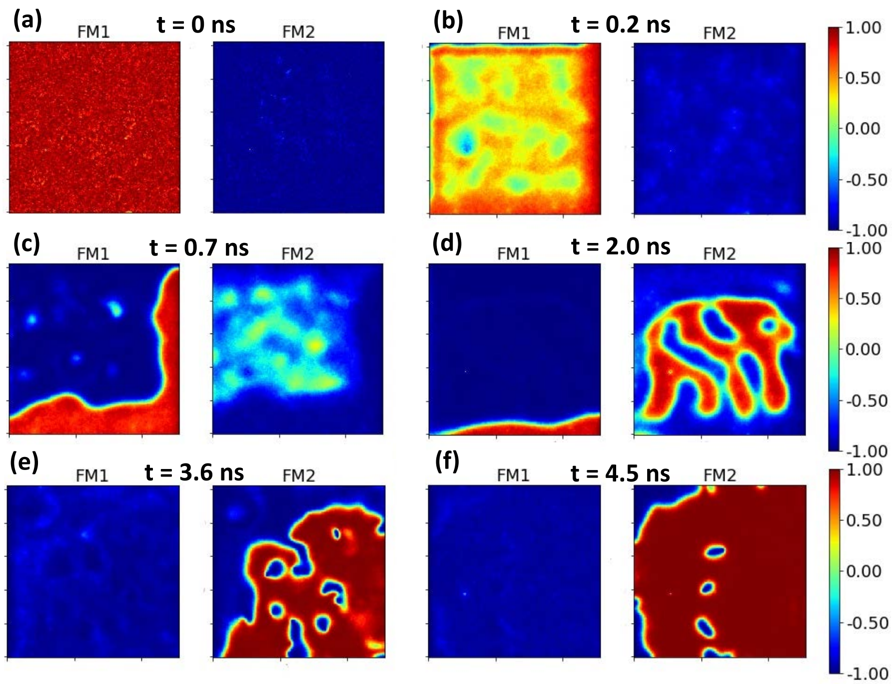

Figure 3: Distribution of m_z components in FM1 and FM2 during $J_x > 0$ SAF switching event with $J_x = 4.4 \times 10^8$ $\mathrm{A/m^2}$ and $J_{\mathrm{RKKY}} = -0.014$ $\mathrm{J/m^2}$. The color scale represents the final state of FM2: red is 'up', while blue is 'down'.

sal of FM2. Note, however, that since the pulse is off and no symmetry-breaking field acts on FM2, the domains are random islands, not structured domain walls.

5. Phase Diagram

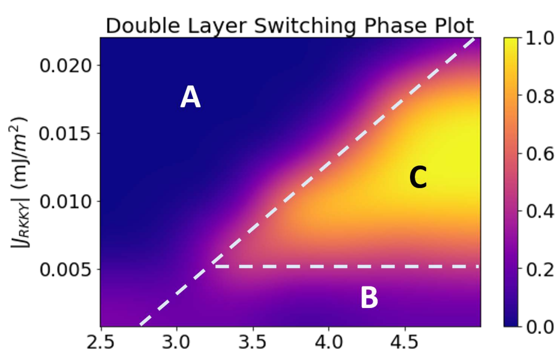

Figure 4: Switching diagram with scale as follows: 1-both layers switch, <1 – only FM1 or neither switch; yellow color shows parameter region with deterministic SOT switching of both layers.

Current-driven switching is commonly studied by plotting switching probability (or final magnetization) as a function of current density and magnetic field to produce 'J-B' phase diagrams. These are useful for identifying successful SOT switching regimes [5, 7]. Evidently, deterministic switching occurs only in a certain range of J-B combinations: a good balance must be achieved to cause a canting in-plane and eventual magnetization reversal, aided by the perpendicular anisotropy and domain chirality driven by DMI[13]. Here we present a slightly modified approach to the switching 'phase space', instead investigating the roles of RKKY coupling strength J_{RKKY} and current density, shown in Fig.4. The color scheme corresponds to switching probability of the SAF: value of 1 represents full SAF switch, < 1 means only FM1 or neither has switched. We identify three separate switching regimes:

- A: current is too weak to compensate for RKKY strength, this is what we call the 'lock-out' state in which neither of the FM layers can be fully switched
- B: weak RKKY doesn't allow FM2 switching process to even begin because it is so strongly repelled from FM1
- C: Switching of the entire SAF (both layers)

Previous'J-B' phase studies show an inverse current-field dependence of SOT switching[13, 7]. However, here a linear relationship is observed between J_{RKKY} and J, but only above a certain threshold value of the RKKY coupling (above the line of region B). Thus, we augment previous claims that RKKY interaction enhances domain wall motion in SAF nanowires[8] by identifying a specific range of parameters in which RKKY actually impedes SOT switching.

6. Conclusions

In summary, after enhancing the model by including Spin-Orbit torque terms in the governing equation, we performed micromagnetic analysis of the field-free magnetization switching dynamics of a synthetic antiferromagnet (SAF). A novel memory structure was modeled addressing the existing SOT-MRAM device challenges. Successful field-free write sequences were demonstrated through numerical simulation of the multi-layer stack. Our micromagnetic results reveal complex multi-domain (non-uniform) switching mechanisms due to complicated inter-layer and intra-layer spin interactions. Finally, we analyzed the range optimal device parameters(coupling strength, applied current) to predict best MRAM performance. These simulation results could prove to be really valuable for the actual fabrication of these stacks with the desired magnetostatic properties leading to deterministic SOT switching.

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