Computational Study of Domain-Wall-Induced Switching of Co/Pt Multilayer

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Abstract—**Nanomagnet logic (NML) emerges as a new field of spintronics. For NML operation, strong external magnetic clocking field pulses are required. The power-efficient generation of such fields is a challenge for magnetic computing. The idea of clocking Co/Pt nanomagnets with stray field from the domain wall of a Permalloy stripe was proposed in the earlier study. Here, we present a micromagnetic investigation of Co/Pt multilayer films that strongly interact with the stray field of a Permalloy domain wall conductor. The simulated domain patterns agree well with experimental results.**

Keywords-Nanomagnet Logic; magnetic domain wall; low power dissipation; micromagnetic simulation;

I. Introduction

Nanomagnet Logic (NML) devices have been an emerging direction of nanoelectronic device research, offering quite attractive benefits, such as non-volatility, low power dissipation and comparability to CMOS technology [1] [2].

Recently, ultra-thin Co/Pt multilayer-dots have been proposed as a promising medium for NML applications [3]. Since the magnetic easy-axis there is perpendicular to the film plane, we call it out-of-plane NML (oNML). There each dot behaves as an island, and one island can communicate with other islands close by through magnetic interactions, which tend to align them in the antiferromagnetic manner.

However, as is known with a large number of dots, the coupling field is insufficient to align all of them perfectly. Errors occur due to thermal fluctuations, process variations, etc [4]. A local clocking is required to drive only a few gates in relatively small area on the chip, which can lead to error-free computing. The local clocking can be generated by pumping current pulses through metal wires buried underneath the dots. However, the calculated current density turned out to be rather high in order to provide a sufficient magnetic field [5]. Consequently, this becomes the bottleneck of NML since these wires bring about a large amount of heat and the power dissipation from the clocking actually dominates over the energy cost resulted from the switching of the dots.

In [6], a new clocking scheme was proposed, where the stray-field of a domain wall is suggested to be used as the

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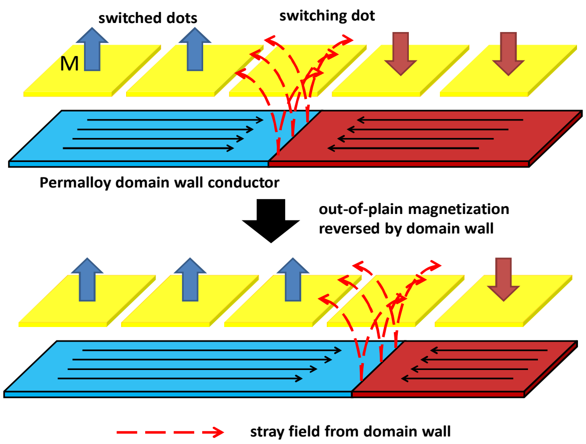

Figure 1. Domain wall clocking: using the out-of-plane stray field from Permalloy domain wall to switch the logic state of single domain Co/Pt nanomagnets and drive the system to computational ground state.

clocking field instead of the current-generated fields, as sketched in Fig 1. This clocking scheme offers the potential to significantly reduce the power consumption from the clocking structure since generating and propagating the domain wall can be achieved with a rather low external field.

Here as an initial attempt toward the complete NML system clocked by domain walls, we present our computational study on the interaction between the Permalloy domain wall conductors (DWC) and Co/Pt films based on our experimental investigations. Our experimentally observation is described in Section II, which suggests strong interaction exist between the two materials. Simulations confirmed this picture and the results are described in Section III. Further discussion is made to suggest the proper geometry for Permalloy domain wall conductor in Section IV. Section V is the conclusion.

II. Experimental Implementation

A domain wall conductor is a nano-scale ferromagnetic structure, in which domain walls are created and propagated. In our experiment, the 20 nm thick Permalloy domain wall conductors were evaporated on a silicon substrate, and it is structured by a lift-off process. The topography of particular

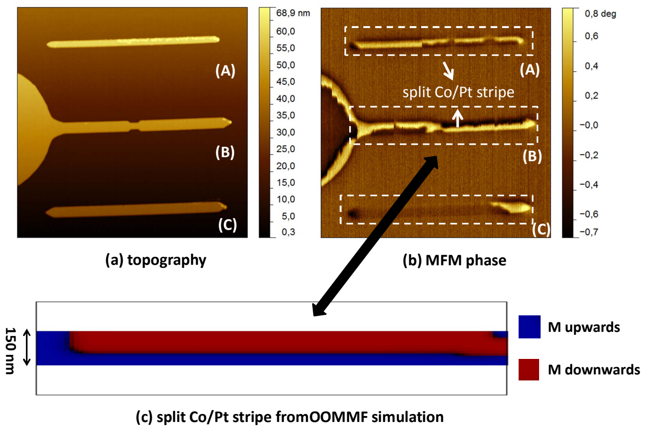

Figure 2. (a) MFM image, showing the topography of the fabricated structure; (b) MFM phase image of the structure showing the interaction of the Permalloy domain wall conductor and the Co/Pt multilayer stripe. (c) OOMMF simulation snapshot: split Co/Pt multilayer stripe, which is consistent with experimental results in (b).

DWCs is shown in Fig. 2 (a). The width of DWC (A) is 140 nm, and 240 nm for DWC (B) and (C). The large pad on the left end of DWC (A) is used to generate a domain wall since it exhibits a multiple domain structure already at low fields and one of the existing domain walls can be pushed into the DWC. The generated domain wall can later be driven out from the pad to the nanowire by an in-plane external field.

Separated by a thin Hydrogen silsesquioxane (HSQ) dielectric layer, the Co/Pt multilayer stack with the composition of $Pt_{4\,nm}$ / $[Co_{0.3\,nm} + Pt_{1.0\,nm}]_8$ / $Pt_{4\,nm}$ is magnetron sputtered at room temperature. A 4 nm Ti layer is evaporated and structured in a lift-off process, serving as hard mask in the dry-etching process.

Initially the structure was saturated by a 700 mT out-of-plane field with an additional x-component of 80 mT. The structure is then relaxed by reducing the external magnetic field simultaneously to zero. The MFM phase in Fig. 2 (b) shows that on top of the Permalloy DWCs, the magnetization of Co/Pt multilayer is reversed, indicating the existing strong interaction between the two layers.

However, it can be seen from Fig. 2 (b) that the Co/Pt multilayer switches incompletely above the DWCs: it split into multiple-domains. In order to have an in-depth understanding of this result, we implement micromagnetic simulations with the most extensively used tool – OOMMF [7].

III. MICROMAGNETIC SIMULATIONS

In [8], we described our computational model tailor-made for Co/Pt multilayer stacks, where point-wise changing magnetic parameters can be defined and then loaded in OOMMF eXtensible Solver Interactive Interface (Oxsii) for three-dimensional simulations.

The structure used in our simulation is illustrated in Fig. 3, where the saturation magnetization of $Ms_{Co/Pt} = 7.0 \times 10^5$ A/m and $Ms_{Permalloy} = 8.6 \times 10^5$ A/m, exchange stiffness of $A_{exch} = 1.3 \times 10^{-11}$ J/m for both materials, and out of plane anisotropy of $K_{Co/Pt} = 3.2 \times 10^5$ J/m^3. These material parameters are

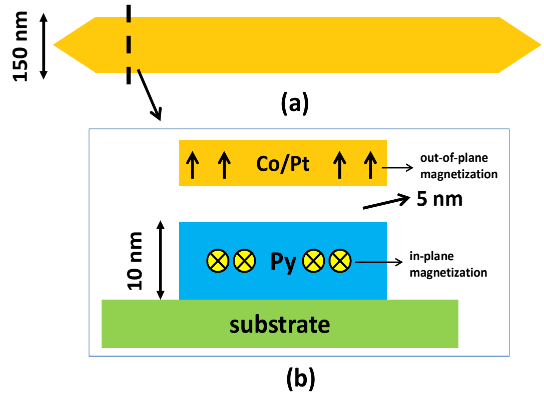

Figure 3. (a) Topview and (b) sideview of the simulated structure.

calibrated by fitting with experimental data [8].

With the similar magnetization procedure as described in experiment, the simulation result is shown in Fig. 2 (c), where the magnetization of Co/Pt multilayer on top of the DWC also appears splitting into multiple domains, due to the relatively large, 150 nm width of the DWC. This simulation result further verifies the strong interaction between the DWC and the Co/Pt multilayer and agrees well with the experimental achievement.

In simulations, we can observe the interaction clearly by initially saturating the Permalloy DWC and Co/Pt multilayer and reversing the magnetization of the DWC with an in-plane external field. As the switching starts from the DWC, a domain wall is created from one end, and it propagates from this end to the other end. The stray-field of this domain wall can reverse the magnetization of Co/Pt layer.

Some snapshots in our simulation are depicted in Fig. 4, where the switching of the Co/Pt layer follows the propagation of the domain wall underneath, proving the strong interaction is sufficient to reverse the magnetization of Co/Pt layer. However, the propagation of the domain wall turned out to be a quite complex behavior (unstable), which causes the complex and uncontrolled magnetization state of the Co/Pt layer.

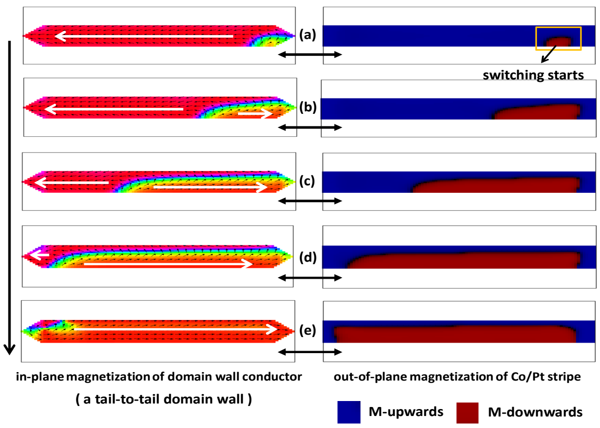

Figure 4. (a) – (e) are five groups of snapshots from OOMMF simulation. Strong interactions between conductor and Co/Pt multilayer were observed: as the domain wall propagates, the switching of Co/Pt follows the trace of domain wall.

IV. DISSCUSION

This paper demonstrated that the stray-field from the domain wall of a DWC can reverse the magnetization in the Co/Pt film. However, in the experiments and calculations described above, the structure of the domain wall was strongly fluctuating upon propagation. It is more challenging to utilize DWCs as the clocking in NML, where well-defined clocking field is required. In order to realize clocking with a propagating domain wall, the following restrictions must be considered:

(1) The stray field from the domain wall needs to be sufficiently strong so as to drive the dots switching (already proved). Yet it is not enough because the clocking field should lie in a certain range: as discussed in [8], if and only if the clocking field is in this proper range, the antiferromagnetic ordering can be obtained. Otherwise the clocking field may either disturb the already aligned ordering (the field is too strong) or make no influence at all (the field is too weak). Meanwhile, the type of the wall (head-to-head or tail-to tail) need to well controlled, since different types of wall generate the out-of-plane field in opposite directions, as illustrated in Fig . 5.

(2) During the wall's propagation, the shape of the wall should be as stable as possible and the stray field should be as homogeneous as possible, acting as a steady-going external field. The DWCs with smaller widths are favored because the domain wall transforms from a vortex pattern to a transverse form as the width decreases [9]. The latter one is a more stable during the motion of the wall and thus more suitable.

Condition 1 can be fulfilled by adjusting the vertical distance (the thickness of the dielectric material as the separation layer) between the two layers or varying the thickness of the DWC. In view of condition 2, a vortex-shaped domain wall should be avoided since such walls have smaller stray field, complex field distribution and complex dynamics. An illustration is given in Fig. 6. Simulations confirm that with a DWC width of 100 nm, a transverse wall is created and keeps its shape during the whole propagation in the DWC.

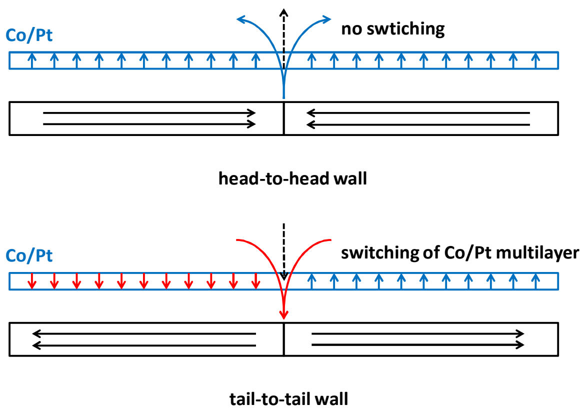

Figure 5. The switching of the Co/Pt stripe is dependent upon the type of domain wall. The stray filed direction of a head- to-head wall is opposite to that of a tail-to-tail wall.

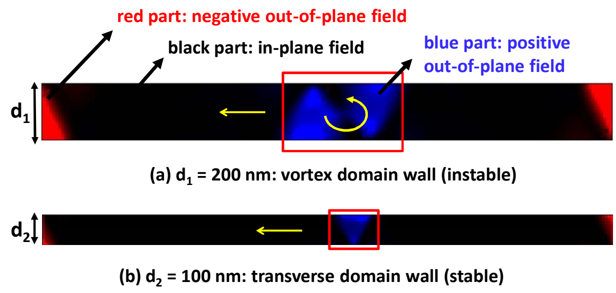

Figure 6. (a) the vortex domai wall in a wider DWC and (b) the more stable transverse domain wall in a 100 nm wide DWC.

V. CONCLUSION

Domain wall clocked NML has the potential to further reduce the power dissipation in NML circuits. In experiments, we observed the strong interaction existing between the Permalloy DWC and the Co/Pt multilayer. Via micromagnetic simulations based on our computational model, we explored the interaction and verified DWC can reverse the Co/Pt multilayer, which agrees well with our experiment result. Further discussion has been made in order to satisfy the preconditions as the domain wall clocking to drive the Co/Pt dots. Our simulations also suggested the proper width of the DWC in order to achieve a more predictable clocking field and prevent the Co/Pt layer splitting into multiple-domains. More experimental and simulation investigations are ongoing.

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