Effect of Segment Length on Domain Wall Pinning in Multisegmented Co/Ni Nanowires for 3D Memory Applications

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Abstract

The interfaces between different materials in multisegmented nanowires act as pinning centers for domain walls, making these nanowires attractive materials for 3D memory devices. Here, the switching events which accompany a domain wall pinning and depinning in two-segmented Co/Ni nanowires with 80 nm in diameter have been simulated for various segment lengths, using the MAGPAR package within the Virtual Micromagnetics environment. Different switching mechanisms of the magnetization were found for nanowires with different segment lengths, contributing to different values of the pinning and depinning fields. Domain wall pinning is caused by the stray field from the Co segment; therefore, the position of the pinned domain wall depends on the cobalt segments length: in case of the smaller segment lengths, the domain wall is pinned at the interface itself, whereas in case of 700 nm segments a 150 nm displacement of the pinned domain wall from the interface is found, consistent with experimental reports. Domain wall pinning is manifested as a plateau in the magnetization curve. In case of nanowires with shorter segments, another plateau is observed that is related to the creation of a magnetic vortex structure. These findings are crucial towards determining the minimum segment length to achieve a higher

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bit density that displays optimal pinning and depinning fields.

Keywords: Micromagnetic Simulation, Cylindrical Nanowire, Domain Wall, Magnetic Memory, Nanofabrication, Domain Wall Motion

1. Introduction

The quest for next generation devices is pushing the boundaries of various technologies such as logic and data storage devices. The racetrack-memory concept [1] based on cylindrical nanowires (CNW) [2] shows considerable potential as a next-generation data storage device. In this memory, multiple bits or magnetic domains can be incorporated in a single CNW by tuning various parameters such as diameter [3] or chemical composition [4, 5]. Experimental studies have shown that in chemically modulated Co/Ni CNWs, the pinning of domain walls occurs near the interface, due to the larger stray field emanating from the cobalt segments [6, 7, 8], which can be exploited to create and manipulate [9] multi-bit states along such a CNW. The concept of such a memory depends on the readout method. In case of magnetoresistance measurements [4], a magnetization along the CNW axis results in the same resistance value, independent of the direction. Hence, two segments are required for each bit. In these studies, the segment length is a consequence of fabrication and characterization requirements, and the fact that above a certain aspect ratio, the stray field strength saturates. For practical purposes, this suggests an upper limit of segment length, but there is no similar criteria for a lower limit.

In this paper we use micromagnetic simulations to systematically study the effect of the segment length on the pinning and depinning of a domain wall at the interface of the nickel and cobalt segments. The domain wall pinning and depinning fields are studied, as well as their absolute difference, defined as a depinning “strength”.

2. Materials and methods

25 The MAGPAR micromagnetic simulations package [10] within the Virtual
Micromagnetics environment [11] was used to search for the ground state of
a two-cylinder magnetic bodies system at different values of the applied field.
Perfect interfaces were assumed, i.e. sharp, flat and no materials mixing. This
is commonly known as finding the relaxed states of the system. The effect of
30 the exchange interaction between the magnetic bodies, i.e. at the boundary,
was considered to be negligible, due to its short range (few nanometers at most)
compared to the large contributions of crystal and shape anisotropies. This
means that the interfaces are sharp: the gradient in composition was considered
to be below or in the order of the element size, which is commonly found exper-
35 imentally for multisegmented CNWs. The long axis of the cylinders coincided
with the z axis in Cartesian coordinates, and, as initial state, the magnetization
of the two bodies was artificially set to the positive z direction ($m_z = 1$) and was
allowed to relax without an external field. Due to the large shape anisotropy
arising from the aspect ratio, most of the z magnetization component remains
40 in that direction in the relaxed state. After this, an external magnetic field was
applied in the negative z direction, to reverse the magnetization of the bodies
and allow the system to relax again. The external field was applied 1 degree
away from the wire's axis and increased in steps of 10 Oe. The simulation was
conditioned to stop, when the magnetization of the bodies reached $m_z \leq -0.95$.

45 2.1. Simulation parameters

The tetrahedral mesh was generated with linear elements of edge length in
the order of the exchange length of cobalt. This is smaller than the smallest
expected feature, which is normally the domain wall width, and big enough to
meet computing memory and time demands. In the case of CNWs of about 100
50 nm in diameter, the domain wall width is in the order of 100 nm [12, 6]. In our
simulations, the memory requirements limited the element size to an average
length of 4.6 nm, which is more than enough to resolve the domain wall width.

Figure 1: The finite element model of a two-segmented cylindrical nanowire is made of two perfect magnetic cylinders with a shared boundary (interface) between them. The magnetic domains are shown in different colors (red and blue).

Table 1: Parameters used in the simulations.

Material	$M_s (T)$	$A (J/m)$	$K_1 (J/m^3)$	$K_2 (J/m^3)$
Nickel	0.61	3.4111×10^{-12}	-0.048×10^5	0.0
Cobalt	1.75	1.32698×10^{-11}	-2.7×10^5	-0.75×10^5

The boundary (interface) between the cylinders is shared, as seen in Fig. 1, which shows the domains of the different magnetic materials in different colors
55 (red and blue).

The magnetic parameters considered in the simulations are summarized in Table 1 and are taken from [13] for fcc Ni (111) and Co (111). Where $M_s (T)$ is the saturation magnetization, $A (J/m)$ is the exchange constant and $K_i (J/m^3)$ are the magnetocrystalline anisotropy constants. The latter de-
60 fine an energy surface, which was oriented (rotated) using the Euler angles $\theta = 0.9, \phi = 0.0, \psi = 0.61$ rad [14].

3. Results and Discussions

3.1. Characteristic Fields

Fig. 2a shows the z component of the magnetization starting from remanence
65 in the positive z-direction, when a field is applied in the negative z-direction,
for different segment lengths. In general, the magnetization reversal depends
on the segment length and a complex interplay of shape anisotropy, crystal
anisotropy (dominant in the Co segment) and the effect of the stray field of
the Co segment inside of the Ni segment. The magnetization inside of the
70 Ni segment usually switches its direction before the one in the Co segment,
due to the smaller exchange and crystal anisotropy energies in the Ni segment.
With the exception of the 50 nm long segments, as the field increases, the z
component of the magnetization slowly reduces, due to open vortices at the
ends of the CNW, which grow in longitudinal size and are shown for 700 nm
75 long segments in Fig. 2b for the states (i) and (ii) in Fig. 2a (the magnetization
in the positive z direction is red and the magnetization in the negative z direction
is blue). This image shows a transversal cut along the center of the nanowire
and the respective end views of each state. As seen in state (ii) from figure
2b, these open vortices extend around 390 nm from the end, and exhibit the
80 “vortex tube” structure reported in other works [15], yet they do not display
the Bloch Skyrmion tube configuration also reported there. After state (ii) a
sudden drop of the magnetization is observed in which, in case of the CNW with
700 nm long segments, the open vortex on the Ni end transforms into a domain
wall and moves from the end to the interface, as has been commonly found for
85 long nanowires [16]. This results in switching the magnetization direction in
the Ni segment. A plateau with almost constant magnetization follows, where
the domain wall remains pinned at the interface (Fig. 2b (iii)) until another
sudden drop in magnetization occurs, which is caused by the depinning and
movement of the domain wall (Fig. 2b (iv)), switching the magnetization in the
90 Co segment. In case of 600 and 700 nm long segments, only one such plateau can
be observed between two switching events. This kind of magnetization reversal

mechanism applies to nanowires with relatively long segments, i.e. longer than 600 nm. The field at which only the nickel segment is switched defines a pinning field and the consecutive switching of the cobalt segment defines a depinning field. The absolute value of the difference of these two fields is defined as a “depinning strength”.

For 400 nm and 500 nm segment length no pinning was observed even after reducing the field step to 5 Oe. Instead of a domain wall nucleation, movement and pinning, the open vortex grows in length towards the interface, and at the value of the switching field, the magnetization in both segments switches. We attribute the fact that no domain wall was nucleated in those cases to the shorter lengths of the segments, leading to less shape anisotropy effects and a coupling with the stray field from the Co segment. If a domain wall pinning exists, it is very unreliable within less than 5 Oe, which is technologically irrelevant in our case.

In case of the 100, 200 and 300 nm long segments, the open vortex in the Ni segment continues growing from the CNW’s end toward the interface, creating a core with magnetization pointing along the z axis and a shell with magnetization in circumferential direction (state (ii) in Fig. 2a and Fig S1). Upon reaching the value of the switching field, the magnetization in the Ni segment switches by coherent rotation and a domain wall appears at the interface.

Notice here that this open vortex reaches the interface before it transforms into a domain wall, that is, the segment length is shorter than the maximum possible open vortex’s extension found for 600 and 700 nm segment lengths, hence the difference in switching mechanisms. This is followed by a plateau during which the domain wall stays pinned at the interface. During this state, the short Co segment has a vortex-like magnetic configuration with the core magnetized along the z axis and the shell rotating about it. After depinning the domain, a jump to another plateau switches only this core in the Co segment. At the end of this second plateau, the shells magnetization also rotates into the z-direction (m_x and m_y) (See supplemental movie). In case of the 300 nm long segments, the first plateau is caused by a change in the magnetization

configuration of both segments to a vortex structure. The second plateau arises after switching the Ni segment at which point a domain wall is pinned at the interface. Finally, the Co segment is switched and the value of the magnetization jumps to the saturation value. We attribute this reconfiguration of the out of axis magnetization (magnetic vortex structure) observed for lower aspect ratio CNWs to the reduced shape anisotropy energy in comparison to the high aspect ratio CNWs with the same crystal anisotropy energy. For further details on the magnetization processes see supplementary movie M1.

The field values for pinning, depinning and depinning strength are plotted in Fig. 3. For 300 nm and below, the increasing depinning field as the segment length is reduced can be understood from an effective field perspective. Aside from the applied in-axis field, crystal and shape anisotropy contribute to the total field. The crystal anisotropy energy surface, favors the magnetization with out of axis components (see section 2.1), acting as an out-of-axis field. The shape anisotropy, on the other hand, depending on the segment length acts as an in-axis (long segments) or out-of-axis (short segments) effective field. So, for longer segments, the contribution from the in-axis field from the nickel segment increases. Therefore, the effective in-axis field acting on the domain wall is higher for longer segments.

The impact of the shape anisotropy effective field can be better appreciated at remanence (zero applied field) in Fig. 2a). As the segment length shortens, the in-axis magnetization (m_z) decreases. In this case, instead of acting on a domain wall, the effective out-of-axis field helps nucleate vortexes at the ends which switch the nickel segment followed by pinning of the domain wall. As the segment length increases, the in-axis effective field opposes the applied field and so, more field is needed to pin the domain wall.

In case of the 600 and 700 nm segment length CNW, the switching mechanism is different, i.e., in this case, there is a propagation of a domain wall from the depinning (end of plateau in Fig. 2a) into the cobalt, for which a lower field is needed, whereas in the 300 nm or less segment lengths, the quasi coherent reversal of the core in the cobalt segment is required (See Fig. 4 and

(a) Magnetization along the nanowire axis (m_z) as function of the applied field (H_{ext}) and segment length: Remanence (i) first switching event (ii) plateau (pinned domain wall) (iii) and second switching event (iv).

(b) Magnetization profile of a CNW with 700 nm long segments sliced in half through the long axis at the different stages labeled in (a).

Figure 2: Simulation results for the magnetization reversal of two-segmented cylindrical nanowires with different lengths. The applied field sweeps from 0 to a negative value. The positive z component of the magnetization (red) points to the left and the negative (blue) one to the right. See supplementary movie M1 for an animated “evolution” of the reversal.

supplementary movie M1).

155 Lastly, the remanence state of the 50 nm segments has zero magnetization

Figure 3: Field values of pinning, depinning and depinning strength for the simulated nanowires. For the 200 nm segment length, both the first (dashed) and the second (continuous) depinning field values are included (See Fig. 2a).

along z , which is unique compared to the other lengths. This zero magnetization is achieved by a curling magnetization along the z axis. When increasing the field the magnetization changes by rotation. The sudden jump in magnetization seen around -700 Oe in Fig. 2a is a transition from curling state to a core-shell structure with the core pointing in the applied field direction.

3.2. Domain wall position

For shorter length segments the simulation results show that the domain wall position is right at the interface, as seen in Fig. 4. Fig. 4 shows the magnetization inside of the CNWs with 100, 200 and 300 nm long segments, sliced in half along the long axis for a magnetic state in the plateau in Fig. 2a, i.e., with a pinned domain wall. For a CNW of 80 nm in diameter and ~ 700 nm segment length, the domain wall pins around 150 nm away from the interface, inside of the Ni segment (Fig. 2b), which confirms previously reported experimental results [6]. In Fig. 2b, the z magnetization component changes direction to the left of the interface, inside the nickel segment. This is attributed to the high stray field of the cobalt, which has a considerable higher saturation magnetization (Table 1) and increases with increased segment length.

Figure 4: Sliced view of the magnetization components of nanowires of 100 nm, 200 nm and 300 nm segment length with a pinned domain wall at the interface (vertical dashed line). Slice goes through the center of the nanowire.

4. Conclusions

Multisegmented CNWs are attractive materials for novel memory devices.

175 An important step forward is understanding of the relation between domain wall pinning at the interfaces and segment length, whereby the latter plays a crucial role in the memory density. Micromagnetic simulations have been carried out on CNWs with 80 nm in diameter and made of Co and Ni segments, where the material interface acts as pinning site for the domain wall. The conditions of
180 the simulations and their agreement with experimental reports suggest that the exchange interaction at the Ni/Co interface plays a minor role in determining the pinning field and strength of the domain wall compared to the cobalt stray field. Several segment lengths were investigated, revealing length-dependent switching mechanisms. They arise from the vortex states at the ends of the
185 nanowires (rods at this length), which are shorter, comparable or longer in length than the length of the segment. In case of the shorter segments (100, 200 and 300 nm), the switching mechanism is a combination of vortex state creation and coherent rotation. For intermediate segment lengths (400 and 500 nm), the open vortex length at the nickel end is similar to the segments'

length and no pinning was observed. In case of the longer segments (600, 700 nm), domain wall nucleation and propagation switches the magnetization. The shortest segment length for which a domain wall could be pinned (i.e. a bit could be created) was found for a CNW of 100 nm segment length, setting a limit on the minimum segment length that could constitute a bit. Below 100 nm, i.e. 50 nm, the remanence is a curling state, which aligns as a core-shell structure with increasing applied external field without the presence of a pinned domain wall. This remanence state has zero magnetization along the z axis, which could be attractive for other applications.

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