Controlled spin-torque driven domain wall motion using staggered magnetic nanowires

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The growing demand for storage, due to big data applications, cannot be met by hard disk drives. Domain wall (DW) memory devices such as racetrack memory offer an alternative route to achieve high capacity storage. In DW memory, control of domain wall positions and their motion using spin-transfer torque are important challenges. In this paper, we demonstrate controlled domain wall motion using spin-transfer torque in staggered magnetic nanowires. The devices, fabricated using electron-beam lithography, were tested using a magneto-optical Kerr microscopy and electrical transport measurements. The depinning current, pinning potential and thermal stability were found to depend on the device dimensions of the staggering nanowires. Thus, the proposed staggering configuration helps to fine-tune the properties of domain wall devices for memory applications.

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I. INTRODUCTION
Spin transfer torque (STT) has been intensively investigated as a tool to reverse the magnetization in a nanoscopic magnet [1–15], generate high-frequency waves in nano-oscillators [16–25] and to move domain wall in magnetic wires [26–47]. Although tremendous efforts have been dedicated to the reversal of magnetization in magnetic materials by STT effect for random access memory application, the storage capacity remains a serious challenge. Proposed schemes like multi-bit per cell MRAM [48] and three-dimensional recording [49] could improve the memory performances in terms of storage capacity but not enough to compete with the existing memories like flash or hard disk drive. Race-track type domain wall memory (DWM) has the potential to combine the best performance of conventional MRAM in addition to the storage capacity.

One of the major problems for adopting magnetic domain wall memory is the accuracy of moving domain wall (DW) in precise positions. When recording each fresh bit of information onto a racetrack, there is considerable uncertainty about where each magnetic domain starts and ends, and an incorrectly-written bit can easily lead to the corruption of all subsequent bits on the racetrack. To overcome these challenges, several ideas were proposed and tested; such as relying on natural defect [50–52] and creating physically notches [53–61]. Other non-geometrical schemes such as modifying locally the magnetic properties of the ferromagnetic nanowire [62–67] using exchange coupling [62,63], metal diffusion [64] or ion-implantation [65,66] were also investigated.

In our previous study, we demonstrated the possibility to stabilize a domain wall in well-defined positions made in stepped nanowires [61]. However, the motion of DW was investigated in materials with in-plane anisotropy using a magnetic field and without electric current. However, the displacement of DW by STT effect is a better approach for the practical implementation of devices for commercial use.

In this study, we demonstrate that one can accurately move DW by a polarized current in (Co/Ni) multilayer with perpendicular magnetic anisotropy. These materials have much higher magnetic anisotropy energy than in-plane type such as NiFe or CoFe alloys ferromagnets and consequently, have better thermal stability.

II. EXPERIMENTAL DETAILS
The magnetic stack consisting of [Co(0.3 nm)/Ni(0.6 nm)] multilayer with 12 repeats was deposited on a thermally oxidized Si substrate. Prior to (Co/Ni) multilayer, a seed layer of Ta (4 nm) and Pt (5 nm) were deposited for better growth which was confirmed by x-rays diffractometer and magnetometry measurements. The whole stack was capped with a Pt (2nm) and Ta (2 nm) in order to maintain the perpendicular anisotropy and avoid corrosion. The magnetic nanowire devices were fabricated using two lithography systems namely electron beam lithography (EBL) and direct-write laser (DWL) lithography. The EBL system was
used to pattern nanowires along with nucleation pads on one end, and the DWL system was used to pattern Au electrodes onto the ends of the nanowires (Fig. 1). Fig. 1(a) shows two small conventional nanowires with off-sets in x and y directions to create a stepped device. The design of a multi-stepped nanowire with 50 \( \mu \text{m} \) length and 1 \( \mu \text{m} \) width is shown in Fig. 1(b). The pad for nucleating magnetic domains is imaged with scanning electron microscopy (SEM). The whole device including the electrical pad for injecting the current is also imaged by SEM in Fig. 1(d).

### III. RESULTS

The (Co/Ni) multilayers with 12 repeats were first investigated as thin films by physical property magnetometry system (PPMS) in out-of-plane geometry. In a prior study on (Co/Ni) multilayers, it was reported that there is a change of the shape of the hysteresis loop as the number of bilayer increases [68]. In this study, we selected the multilayer of 12 repeats which has a perpendicular magnetic anisotropy and small magnetic domains. The tail in the hysteresis loop shown in Fig. 2(a) is the result of an increase of magnetostatic energy which competes with the magnetic anisotropy energy. The presence of the perpendicular magnetic anisotropy is confirmed by magnetic force microscopy (MFM) images shown in Fig. 2(b) and Fig. 2(c) for the cases of 8 and 12 bilayer repeats.

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**FIG. 1.** (a) The design of a staggered magnetic nanowire with the x and y off-sets represented by \( \lambda \) and \( d \), respectively. (b) magnetic nanowire with multi-step design. The length and width of the nanowire were fixed to 50 \( \mu \text{m} \) and 1 \( \mu \text{m} \), respectively. Scanning electron micrograph image of a part of the fabricated device before (c) and after (d) making the electrodes for applying the electric current. At the edge of the nanowire, a large area is created by lithography during the fabrication for easy nucleation of magnetic domains.
It is clear from MFM images that the size of magnetic domains is strongly reduced for the sample with 12 repeats as compared to that with 8 repeats. All the measurements were carried out at room temperature. Although the saturation of the unpatterned sample requires an external magnetic field of less than 1 kOe, after patterning the nanowires, the magnetization reversal occurs at much higher field. To be able to observe the motion of domain wall in nanowires shown in Fig. 2(d) under a reasonable magnetic field (less than 1 kOe), the samples were annealed at 240 °C for 30 minutes. The procedure of investigating domain wall motion and magnetic reversal in nanowire is schematically shown in Fig. 3(a). The device is under an external perpendicular magnetic field (H_{per}) and the pulsed current is also applied along the nanowire. Simultaneously, magneto-optical Kerr effect (MOKE) microscope is positioned above the device to image the magnetic domains. For better contrast, the recorded image was subtracted from a reference one, which is taken at the saturated state. The hysteresis loop shown in Fig. 3(b) is the result of magnetization reversal in a conventional nanowire without nano-constriction but with the same dimensions as the one shown in Fig. 1(b). For a conventional nanowire (without constriction), a swift change of magnetic state from up-state (state 1) to down-state (state 2) was observed. Even with a very slow scan of the magnetic field, it was not possible to stabilize a DW at any position within the nanowire with the dimension discussed above. This result was expected and reported in a previous study for the cases of NiFe and CoFeB ferromagnetic materials with in-plane magnetic anisotropy [61]. In the second step of this study, we investigated the pinning of DW in stepped nanowires. The hysteresis loop of the nanowire is plotted in Fig. 4(a). Even with a fast scan of the applied magnetic field, jumps in magnetization reversal could be clearly seen and the magnetic states were captured by MOKE microscope. The first jump which occurs at around 500 Oe indicates the creation of DW at the nucleation pad, stopped at the first step as shown by the inserted MOKE image. The second jump at slightly higher applied magnetic field is the result of the creation of a magnetic domain from the right side of the nanowire. It has to be pointed out that this magnetic state is not due to the propagation of the firstly created domain at the left side. It is believed that the pinning strength at the constricted area is higher than the magnetic field needed for domain nucleation on the right side. It is important
FIG. 3. (a) The polar MOKE signal for a conventional nanowire (without steps) showing a sharp change of MOKE signal at about 0.9 kOe applied magnetic field. An indication of only two possible states as shown in (b) for state 1 where the magnetization of the nanowire is aligned in up direction (bright contrast) and in (c) state 2 where the nanowire has its magnetization pointing in down direction (dark contrast).

to note that the magnetic field from the electromagnet is covering the whole device area and as a result, the nucleation may happen at any part of the device. Finally, at a larger magnetic field, the whole device magnetization becomes aligned in the up direction. There are a few steps where DW could not be pinned or blocked.

For DW motion by a magnetic field, good control of the strength of the effective pinning field at the stepped region is necessary. This can be achieved by intrinsic materials properties governing the domain wall dynamics such as anisotropy field, saturation magnetization and exchange stiffness or by the device geometry or edge roughness. In this study, the fabricated devices have the same steps dimension i.e. the same values of d and l shown in Fig. 1(a). As a result, the pinning field offered by each step is the same. Therefore, despite our effort to check several devices for stabilizing DW at each step by magnetic field, we were not successful in the controlled motion of the domain wall, stopping at each step. However, for a few particular devices of (Co/Pt) multilayer case, we could see the pinning of DW at each step [69].

As our objective was to stabilize DW at each step in the designed device, we carried out a similar study by applying an electric current between the two electrodes as shown in Fig. 4(b) for values of d and l of 600 nm and 100 nm, respectively. To start this series of experiments, we first created a magnetic domain near the small pad (nucleation pad) by applying a small magnetic field in the out-of-plane direction and shown in Fig. 3(a). The white arrow indicates the first step within the nanowire from the left side where DW is stabilized, and the small dotted lines show the other nanoconstrictions for
FIG. 4. The polar MOKE signal for a stepped as shown in Fig. 1(b). Insert are the MOKE images of different magnetic states at different applied magnetic fields. (b) MOKE image where domain wall is stabilized by a magnetic field as the first step. (c)–(g) other states obtained by applying different current magnitudes. The current is flowing along the nanowire while the magnetic field is applied perpendicular to the device plane.

To investigate the motion of DW by spin-transfer torque, the magnetic field was removed and a pulsed electric current with increased magnitude and fixed pulse width of 100 μs was applied. The displacement of DW to the second step could be seen at 4.38 mA as shown in Fig. 4(c).

To move DW to step 3, an electric current of 4.235 mA was applied (with a small assisted magnetic field of 60 Oe) by keeping the pulse width at 100 μs [Fig. 4(d)]. The other states shown in Figs. (f–g) could also be obtained under the same magnetic field of 60 Oe and by a small change of the current pulse. The device could be left for a few hours and we did not see any change of the magnetic state (position of DW). Interestingly, the states discussed above could be obtained under the same conditions demonstrating their reproducibility.

In this study, we defined the depinning current $i_{\text{dep}}$ as the minimum current magnitude for moving DW from one state to the other. Both the devices shown in figure 5(a) exhibit a dependence of $i_{\text{dep}}$ on the applied assisting magnetic field $H_{\text{per}}$ for a fixed...
current pulse width of 100 μs. In the case of the device with \( d = 600 \text{ nm} \) and \( \lambda = 100 \text{ nm} \) (black dots), \( i_{\text{dep}} \) is larger but shows a weaker dependence with \( H_{\text{per}} \). In the case of \( d = 200 \text{ nm} \) and \( \lambda = 0 \text{ nm} \), \( i_{\text{dep}} \) is less and an exponential decay trend is seen (blue dots). This difference in the trend of \( i_{\text{dep}} \) with the applied magnetic is worthy of investigating and possibly could be due to the domain wall configuration in the nanoconstriction region.

After investigating the possibility to pin DW at defined positions by an applied electric current, we focused on evaluating its stability. Firstly, the DW was positioned in one step as described above and by synchronizing MOKE microscope, the applied current and the magnetic field, the time before the depinning occurs was measured. Fig. 5(b) is a plot of the time versus the applied magnetic field for the device with \( d = 600 \text{ nm} \) and \( \lambda = 0 \text{ nm} \). It can be noticed that the time \( t \) follows an exponential decay function similar to Sharrock’s law [70] which is applied here to DW and not the domain itself. In fact, once the magnetic domain expands or vanishes (becomes unstable), DW itself will either move or disappears. The time \( t \) can be expressed as

\[
t = \tau_0 \exp \left[ S \left( 1 - \frac{H}{H_0} \right)^\alpha \right]
\]  

(1)

To get a better fit and extract some valuable information on thermal stability of DW, Eq. (1) is rewritten in a linear form [Eq. (2)].

\[
H = H_0 - B \left[ \ln \left( \frac{f_0 t}{\ln(2)} \right) \right]^{2/3}
\]  

(2)

where \( f_0 \) is the attempt frequency, the parameters \( H_0 \) and \( B \) are the fitting parameters which are related to the stability factor \( S \) through the relation

\[
S = \left( \frac{H_0}{B} \right)^{3/2}
\]  

(3)
FIG. 6. Depinning current density as a function of the uniaxial magnetic anisotropy for a magnetic nanowire with d = 600 nm and two λ values of 100 and 200 nm. Inset are the magnetic moments profile near the nanoconstriction. The two cases of applied current densities below and above $J_{\text{dep}}$.

From the best fit to the data shown in inset of Fig. 5(b), one could obtain a stability factor of about 50. As discussed above, there are several ways to reduce the current for DW motion. For memory application, it is essential to reduce the depinning current. Similarly, adding a spin-orbit torque effect to STT is one solution. As shown from the thermal stability factor, which is much higher than what is required for the application, one could reduce the magnetic anisotropy energy and yet the DW will remain stable for more than 5 years. The dependence of the depinning current density $J_{\text{dep}}$ on the uniaxial magnetic anisotropy is plotted in Fig. 6 for two devices. The calculation was carried out using micromagnetism formalism [61]. It can be seen that the staggered nanowire design offers the possibility to adjust $J_{\text{dep}}$ by changing λ for example. For $d = 600$ nm, increasing the off-set in γ-direction helps the reduction of $J_{\text{dep}}$. Thus, a staggered-nanowire offers several possibilities to tune the performance of domain walls for memory applications.

IV. SUMMARY

In this paper, we have demonstrated controlled domain wall motion in magnetic nanowires using spin-transfer torque and a staggered design. The depinning current depends on the design parameters, d and λ. The dependence of depinning current on the applied external magnetic field shows two different behaviors in devices with different d. The thermal stability and depinning current can be tuned by adjusting the design parameters of the staggered nanowires, indicating that the staggered magnetic nanowires offer better control of domain wall memory design.

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