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In-plane magnetic field pulse driven perpendicularly magnetized racetrack memory

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Abstract

Field driven racetrack memory, an in-plane magnetic field pulse induced Bloch type or Neel type domain wall motion, is numerically and analytically investigated. Moreover, multiple Bloch type or Neel type domain wall displacement are also observed by applying in-plane magnetic field pulses. Due to the interfacial Dzyaloshinskii-Moriya interaction, chiral multiple Neel type domain walls are naturally nucleated. By performing this technique, we can distinguish Neel or Bloch type domain walls. In addition, we show that multiple Neel type domain walls with the same chirality can be served as a field driven racetrack memory devices.

1. Introduction

Recently, a wide range of devices based on domain wall (DW) with perpendicular magnetic anisotropy (PMA) has been proposed including high-density data storage and logic devices. Because of its great potential for applications, a great deal of techniques to manipulate DWs have been extensively developed such as field driven, current-induced, and spin-orbit torque driven DW motions for the last decade [1,2]. The conventional approach of using external magnetic fields parallel to the magnetization in the domains has been plagued by the insurmountable problem that the magnetic fields shrink or expand magnetic domains and then it leads to a collapse of the domains. However, this approach is well established with high DW velocities (ultrafast device operation speed) and allows for non-contact writing without any electric contact. As an alternative way to drive DWs, the current-induced DW motion due to the spin torque effects allow for synchronous motion of multiple domains and it is a fascinating way to efficiently manipulate the magnetization configuration in potential novel devices. However, the required high currents face intrinsic problems, such as Joule heating owing to Ohmic losses [3].

In order to synchronously manipulate multiple DWs using magnetic fields and solve the dilemma of the conventional field driven DW motion, a radically different approach using a perpendicular magnetic field pulse on an in-plane magnetized nanowire is experimentally and theoretically demonstrated lately [4]. In our previous approach [4], we used so called non-equilibrium spin dynamics, which give us totally different results from the equilibrium one. The DW in the in-plane magnetization nanowire moves by perpendicular field, and we successfully explained the un-expected phenomena and demonstrated. This outstanding synchronous precessional motion of multiple DWs can shift the paradigm of the field driven DW motion. Few hundreds nanometer displacements are clearly observed and the energy dissipation of the system is quite competitive even with the theoretically calculated DW motion by the spin transfer torque on a defect-free nanowire. However, for a PMA nanowire based on heavy metal / ferromagnetic multilayer, spin-orbit torques introduce a new phenomenon, the so-called "chirality dependent Neel type DWs". [5]

2. Domain Wall Dynamics with In-plane Pulse Field

In this study, we analytically and numerically demonstrate synchronous DW motion by applying in-plane magnetic fields on a perpendicularly magnetized nanowire. It must be emphasized that we applied in-plane field, not a perpendicular field to the perpendicularly magnetized nanowire. At a glance, there is nothing happened because there is no changes in the Zeeman energy with in-plane field. However, we found several interesting phenomena with our unusual field configuration. The all interesting phenomena happened within a few nano seconds, where the spin dynamics are belong to the non-equilibrium state. After that the spin dynamics returns to the equilibrium state, and all interesting phenomena are disappeared. Therefore, we focused to the non-equilibrium spin dynamics.

First, the precession torque exerts to rotate magnetic domains and domain walls. As a result, the direction of the DW displacements depends on the direction of the magnetic field and the chirality of the DW. Therefore, according to this method, the two types of the DW (Bloch or Neel wall) and even the in-plane tilting angle of the DW can be distinguished by the response to the external magnetic field. It must be emphasized that the DW types or tilting angle of DW is not easy to determine by any other experimental tools, except some special cases. By combined with one-dimensional collective-coordinates model and micromagnetic simulations, we can distinguish the DW types and tilting angles.

Second, the time scale of such non-equilibrium phenomena is order of a few nano-seconds. The one-dimensional collective-coordinates model reveal the time scale is determined by the materials parameters. Therefore, the interesting DW motion only occurs on the timescale of the non-equilibrium dynamics. After a few nano-second, the DW returns to the equilibrium state.

Finally, if we include the interfacial Dzyaloshinskii-Moriya interaction, the chiral Neel type

DWs are nucleated and then the synchronous multiple Neel wall motions are clearly observed by applying in-plane magnetic field pulses along the *y*-direction. From this technique, we are able to distinguish the Neel type or Bloch type DWs, since Neel type only reacts by the in-plane field pulse along the *y*-direction, while Bloch wall will response with the *x*-direction in-plane field.

We showed some highlights of our finding. Figure 1(a) and (b) show the chirality dependent Bloch wall displacements. Two Bloch Walls with opposite chirality are located at the center of nanowires. For the DWs, the in-plane magnetic field pulses are applied along the *x*-direction. After t = 2 ns, the snapshots of the spin configurations are taken again. Fig. 1(c-e) indicate the Bloch wall displacements for various physical parameters: (c) for the amplitude of B_x, (d) the magnetic damping constant, and (e) the rise time of the applied in-plane field pulse. All straight lines indicate the DW displacements from the one-dimensional collective coordinate model.

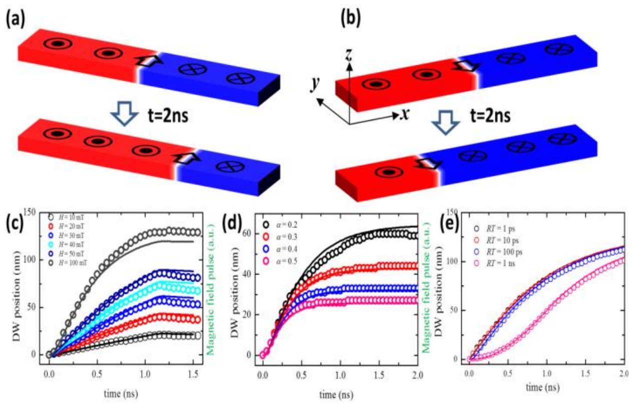

Figure 1 (a) and (b) Chirality dependent BWs displacements. The calculated BW displacements with various physical quantities: (c) the amplitude of the B_x, (d) the magnetic damping constant, and (e) the rise time of the in-plane magnetic field pulse as a function of the simulation time.

Figure 2 indicates another example of our first finding. The synchronous multiple BWs motion by successive in-plane magnetic field pulses along the *x*-direction. The figure is consists of two parts. Upper part is for two BWs motion and downer part is for three BWs motion. We set-up two/three Bloch wall with the same chirality as an initial condition. It must be mentioned that it is not easy in the real experiments, however, the same chirality DW can be naturally formed with a finite iDMI system (not shown here). Since the basics principle of the DW motions are exactly the same, we showed only two (or three) same chirality Bloch walls cases. Since the DW motion under the perpendicular in-plane pulse field are determined by the field direction and the DW chirality, all DW with the same chirality moves to the same directions. In order to trap DWs small notches (5×5 nm^2, 200 nm spacing) are arranged along the nanowire. Finally, two or three BWs are clearly displaced by applying *x*-direction in-plane magnetic field pulses and they are trapped at the neighbor notches. Therefore, we successively demonstrate multiple BWs motions by using in-plane field pulses.

3. Conclusions

An in-plane magnetic field pulse induced Bloch or Neel type domain wall motions, pulse field driven racetrack memory is numerically and analytically investigated by performing one dimensional collective coordinate model and micromagnetic simulations. Firstly, multiple Bloch type or Neel type domain wall displacement are clearly observed by applying in-plane magnetic field pulses. Because the interfacial Dzyaloshinskii-Moriya interaction, chiral multiple Neel type domain walls can be nucleated. By using this in-plane field driven BW or NW motion, we distinguish Neel type or Bloch type domain walls. Furthermore multiple Neel type domain wall with the same chirality can be also realized and it can open a new path to develop a field driven racetrack memory.

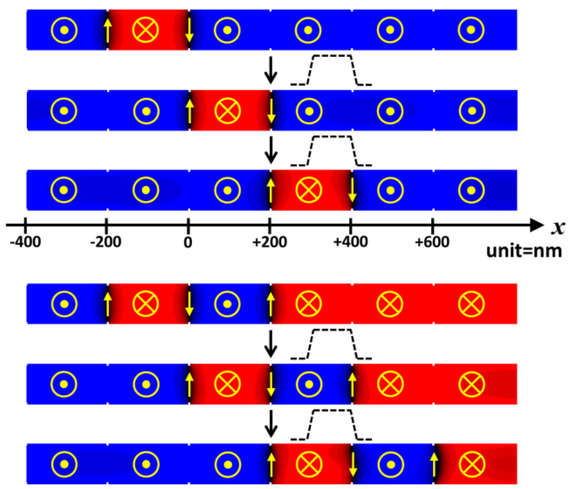

Figure 2. Upper part – two BWs with the same chirality displacement by B_x. The successive pulses are introduced and the BWs are moved along the *x*-direction. Downer part - three BWs with the same chirality displacement by B_x. The successive pulses are introduced and the BWs are moved along the *x*-direction. Small notches (**5 × 5** nm^2, 200 nm spacing) are sequentially located along the nanowire.

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Appendix