Domain Wall Velocity Characteristics of Chirality-Optimized Spintronic Structure

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Abstract
In this letter, a standard design of spintronic device based on multilayer structure was considered to study the effects of the current density in this structure on the domain wall velocity and Dzyaloshinskii-Moriya interaction (DMI). The performance of the spintronic device can be optimized by determining critical thresholds of the binding energy that maintains the domain walls at the crystalline structure defects. It is approximately typical behavior as the increasing current density provides better electrical environment for the DMI with maximum dynamic or diffusion current flows and minimum leakage current flow at the interfaces.

Keywords: Spintronics; Domain walls; Dzyaloshinskii-Moriya interaction (DMI); Walker breakdown
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1. Introduction

Domain walls (DWs) dynamics are a fundamental in magnetic materials physics alongside with tends towards spintronics and their applications. The domain wall is the narrow transition region (at the nanoscale) that separates magnetic domains of different directions [1,2]. Understanding and adjustment of the domain wall velocity under external effects is the key of the magnetic material behavior. The wall motion obeys several fundamentals and principles in physics. First, the minimum energy principle states that the wall moves to reduce the total energy of the system, especially Zeeman energy related to the applied magnetic field. The application of an external magnetic field leads to initiate a magnetic pressure [3-5]. Second, the Pinning phenomenon is an obstacle against wall movement due to the structural defects (holes or impurities). This phenomenon requires the wall to exceed a critical field threshold (Depinning field). At weak fields, the thermal creep dominates as the walls move slowly according to a logarithmic behavior [6]. At strong fields, the flow system is considered as the velocity is linearly proportional to the magnetic field [7]. Furthermore, in solids, the electronic current flowing or Eddy currents cause friction that limits the acceleration [8-10]. Practically, the walls achieve a maximum velocity up to several kilometers per second determined by the spin waves, which represent the Walker breakdown at which the wall loses its structural stability [11,12].

In this letter, the effect of current density flowing through a multilayer spintronic structure on the domain wall velocity and Dzyaloshinskii-Moriya Interaction (DMI) induced in such structures.

2. Experimental Part

According to the multilayer structure schematically shown in Fig. (1), the aim of this work is to achieve fine control of each layer individually to enable the design of the DMI and hence the magnetic chirality. In order to produce accurate and repeatable deposition of these nanostructures, magnetron sputtering technique was used to do so as the optimum choice for the academic and industrial purposes. This technique is preferred as the high-quality epitaxial or polycrystalline films can be deposited at relatively low temperatures, which maintains the interfaces. This technique provides accurate control of layer thickness down to angstrom (Å) scale at steady deposition rates. This technique can also deposit a wide range of heavy metals (Pt, Ta, W), magnetic alloys (NiFe, CoFeB), and insulators (MgO).

A dc magnetron sputtering technique was used to prepare the multilayer structure on a (111) silicon wafer as a substrate. This system contains two cathodes maintained on the upper flange of the deposition chamber with only one anode on which the silicon substrate was placed [13-15]. The layers of ferromagnetics 1 and 2, spacer, and heavy metal were sequentially deposited after 180, 60, and 120 minutes, respectively, at room temperature. The discharge current was 40 mA using argon gas at 0.08 mbar pressure and flow rate of 50 sccm.

Thermal annealing is an important step in the fabrication process of the proposed multilayer structure. It was carried out under vacuum at 350°C for one hour in inert environment of argon. Consequently, the amorphous CoFe layers convert into crystalline, which supports the perpendicular magnetic momentum as well as the magnetic resistance ratio.

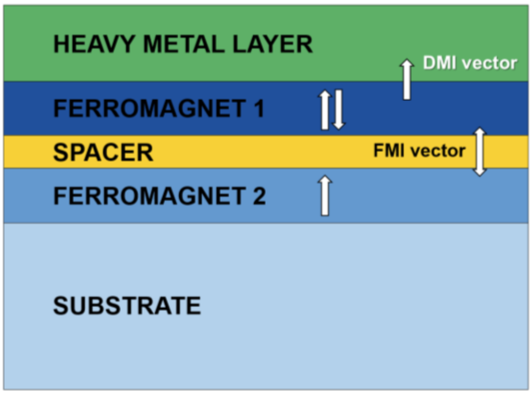

Fig. (1) Schematic diagram of the multilayer structure prepared in this work with labels showing layers and active regions

3. Results and Discussion

Figure (2) shows the variation of the domain wall velocity with current density as three regions can be observed. In the first region ($<3x10^{11}$ A/m^2), a depinning threshold at $0.5x10^{11}$ A/m^2 is apparent as the current density is critical and insufficient to overcome the binding energy that maintains the domain walls at the crystalline structure defects (pinning sites). In the second region ($3\text{-}6x10^{11}$ A/m^2), a sharp and semi-linear increase in the domain wall velocity to represent a creep regime or steady-flow regime as the SOT begins to move the magnetic walls much more increasingly. In the third region ($>6x10^{11}$ A/m^2), the domain wall velocity saturates at 1 m/s due to Walker breakdown or increasing sample temperature due to Joule heating effect that suppresses the uniform or steady dynamics.

Figure (3) shows the variation of the DMI energy density with current density as a continuous increasing behavior is observed. The curve began to increase semi-linearly at low current densities and then tended to saturate at higher current densities as a result of the magnetic characteristics of the thin layers when subjected to high electric currents that have sufficient effects on the stability of the magnetic structures (like skyrmions). This behavior also refers to the existence of physical limits for the effect of current on the interaction intensity. It is approximately typical behavior as the increasing current density provides better electrical environment for the DMI with maximum dynamic or diffusion current flows and minimum leakage current flow at the interfaces.

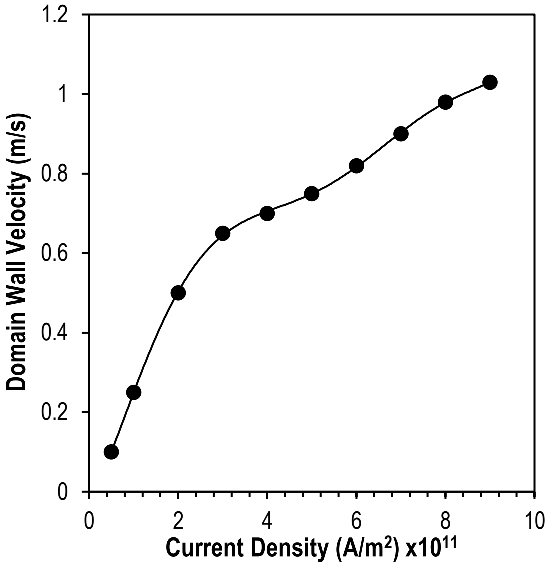

Fig. (2) Variation of the domain wall velocity with the current density for the Pt/FM1/SPACER/FM2/Si structure

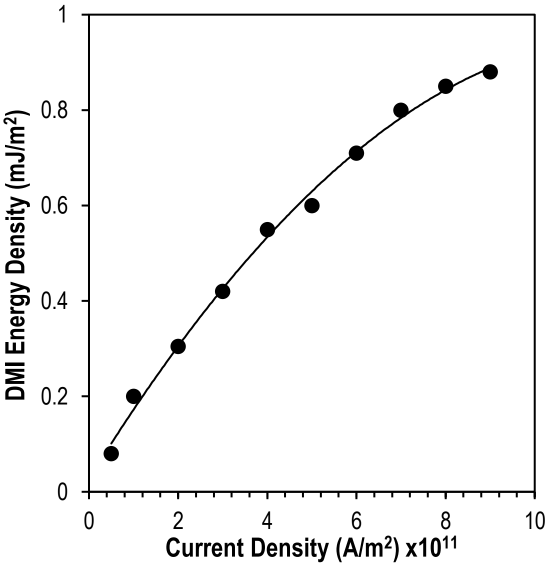

Fig. (3) Variation of the DMI energy density with the current density for the Pt/FM1/SPACER/FM2/Si structure

4. Conclusion

In conclusions, the domain wall velocity was semi-linearly increasing with current density to reach a saturation at $6x10^{11}$ A/m^2 due to the Walker breakdown phenomenon. The highest ultrahigh velocity of 10^3 m/s was achieved at low threshold current density ($1.2x10^{11}$ A/m^2). These results reveal the possibility to accurately design the spin chirality leading to drastic development in ultrafast and low-energy spintronics.

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