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Antiferromagnetic domain wall motion driven by spin-orbit torques

Takayuki Shiino[1], Se-Hyeok Oh[2], Paul M. Haney[3], Seo-Won Lee[4], Gyungchoon Go[4], Byong-Guk Park[1], and Kyung-Jin Lee[2,4,5]

[1] Department of Materials Science and Engineering, KAIST, Daejeon 305-701, Korea
[2] Department of Nano-Semiconductor and Engineering, Korea University, Seoul 136-701, Korea
[3] Center for Nanoscale Science and Technology, NIST, Gaithersburg, Maryland 20899-6202, USA
[4] Department of Material Science and Engineering, Korea University, Seoul 136-701, Korea
[5] KU-KIST Graduate School of Converging Science and Technology, Korea University, Seoul 136-713, Korea

Abstract

We theoretically investigate dynamics of antiferromagnetic domain walls driven by spin-orbit torques in antiferromagnet/heavy metal bilayers. We show that spin-orbit torques drive antiferromagnetic domain walls much faster than ferromagnetic domain walls. As the domain wall velocity approaches the maximum spin-wave group velocity, the domain wall undergoes Lorentz contraction and emits spin-waves in the terahertz frequency range. The interplay between spin-orbit torques and the relativistic dynamics of antiferromagnetic domain walls leads to the efficient manipulation of antiferromagnetic spin textures and paves the way for the generation of high frequency signals from antiferromagnets.

Antiferromagnets are ordered spin systems in which the magnetic moments are compensated on an atomic scale. The antiferromagnetic order and consequent zero net magnetic moment are maintained by antiferromagnetic exchange coupling of neighboring spins. Any external disturbance competes directly with the large antiferromagnetic exchange, which results in magnetic excitations in terahertz frequency ranges [1]. Furthermore, an antiferromagnet has no magnetic stray field, which is beneficial for integrated circuits because the stray field is a primary source of detrimental magnetic perturbations [2, 3]. These attractive features of antiferromagnets have led to the recent development of antiferromagnetic spintronics, an emerging research field which pursues the use of antiferromagnets as active elements in spintronic-based devices [4].

The principal discipline of antiferromagnetic spintronics is the robust detection and manipulation of the antiferromagnetic order. The antiferromagnetic order can be electrically probed through the (tunneling) anisotropic magnetoresistance effect [5] or the spin pumping effect [6, 7]. Significant progress has also been made on the manipulation of the antiferromagnetic order, using both charge and spin currents [8]. Conventional spin-transfer torque enables current-driven manipulation of antiferromagnetic spin textures such as antiferromagnetic domain walls [9-11] and antiferromagnetic skyrmions [12, 13]. We note however that most previous studies on current-driven manipulation of antiferromagnetic order have neglected spin-orbit coupling.

We theoretically investigate spin-orbit torque (SOT) driven antiferromagnetic domain wall (AF-DW) motion in antiferromagnet/heavy metal bilayers in the presence of interfacial Dzyaloshinskii-Moriya interaction (DMI). Based on the collective coordinate approach [10], we obtain that the steady-state velocity (v_{DW}) is $v_{DW,1} = -\pi\gamma\lambda B_D / 2\alpha$, where α is the Gilbert damping, γ is the gyromagnetic ratio, λ is the DW width, and B_D is the magnitude of damping-like SOT. To verify the analytical results, we perform atomistic numerical simulations based on the Landau-Lifshitz-Gilbert equation [14]. The symbols in the Fig. 1(a) show numerical results of vDW as a function of J. As predicted by the analytical equations, a Bloch DW does not move whereas v_{DW} of Néel DW linearly increases with J in the low current regime. However, we find that v_{DW} saturates in the high current regime with emitting spin-waves (Fig. 1(b)). This can be explained as follows: A damping-like SOT induces an asymmetric domain

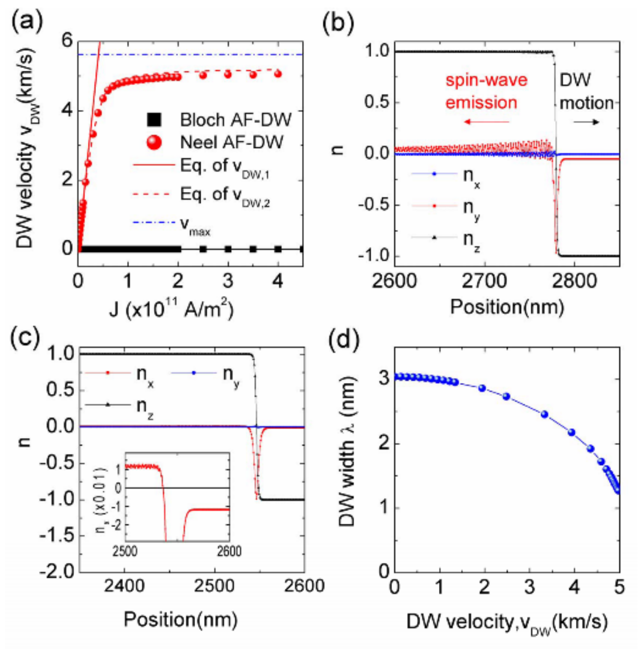

Figure 1. SOT-driven AF-DW motion (field-like SOT = 0) (a) DW velocity v_{DW} vs. current density J. (b) Configuration of Neel-type AF-DW during the steady motion at J = 2.0 × 10^{11} A/m^2. (c) Configuration of Neel-type AF-DW at J = 0.5 × 10^{11} A/m^2. Inset shows n_x component. (d) DW width λ vs. DW velocity v_{DW}.

tilting (inset of Fig. 1(c)), resulting in a difference of exchange energy between the left and right sides of AF-DW. As the wall moves faster, the wall width λ shrinks more (Fig. 1(d)). As λ approaches a few lattice constants, AF-DW is unable to sustain its exchange energy and starts to emit spin-waves towards its rear to release the energy. Therefore, the spin-wave emission serves as an additional energy dissipation channel and slows down the wall motion. The velocity limit of AF-DW due to spin-wave emission can be described by the relativistic kinematics [3]: it undergoes Lorentz contraction as v_{DW} approaches the maximum spin-wave group velocity (v_{max}), and saturates to v_{max}. Thus, the relativistically corrected v_{DW} is given as, $v_{DW,2} = v_{max}\ [1-(\lambda/\ \lambda_{eq})^2]^{1/2}$, where λ_{eq} is the equilibrium λ. We find that $v_{DW,2}$ describes the numerical results reasonably well (Fig. 1(a)). We also find that the frequency of emitted spin-waves is in the terahertz ranges. The power of this THz signal based on the spin pumping and inverse spin-Hall effect is of the order of μW, which is measurable.

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