Physics Letters A 379 (2015) 367–371

Contents lists available at ScienceDirect

Physics Letters A

www.elsevier.com/locate/pla

Chargeless spin current for switching and coupling of domain walls in magnetic nanowires

C.L. Jia [a,b], J. Berakdar [b,*]

[a] Key Laboratory for Magnetism and Magnetic Materials of MOE, Lanzhou University, Lanzhou 730000, China
[b] Institut für Physik, Martin-Luther Universität Halle–Wittenberg, 06099 Halle (Saale), Germany

ARTICLE INFO

Article history:
Received 21 June 2014
Received in revised form 10 November 2014
Accepted 19 November 2014
Available online 20 November 2014
Communicated by R. Wu

Keywords:
Spin-polarized transport
Spintronics
Dynamics of domain structures
Magnetoelectric effects

ABSTRACT

We study theoretically the effect of a pure spin current in a quantum wire on magnetic domain walls (DWs). We find that a pure spin current acts on DWs with an effective spin-transfer torque that depends on the mutual DWs separation which results in picosecond magnetization dynamics. Spin-dependent interferences due to spin-current scattering from DWs result in a spin-orbital interaction of the carriers whose strength is determined by the orientations and the spatial separation of DWs. This amounts to an effective dynamical magnetoelectric coupling.

The interaction between charge currents and localized magnetic textures, e.g. domain walls (DWs), is attracting intense research as a paradigm for the interplay of charge and spin degrees of freedom but also due to novel spintronic applications [1–6]. In general, current-induced magnetization dynamics is fairly well understood and can be quantified by means of the Landau–Lifshitz–Gilbert (LLG) equation [7,8]. Within this phenomenological description, the presence of DWs leads to two torques contributions [10,11]. (1) An adiabatic spin-transfer torques (STT): In this case the carriers' spins follow adiabatically the direction of the local magnetization. (2) The nonadiabatic contribution gains importance when the carriers wave length is comparable to the spatial extension of the non-collinear region. The boundary between these two cases is, however, blurred and depends in particular on the damping of the precessional motion. For applications, the required high current density poses an obstacle and entails in particular high energy consumption and dissipation.

A possible advance is expected from utilizing a pure carrier spin current, i.e. a flow of carrier spin angular momentum. The basic idea is that the energy scale for transversal spin excitations ($\sim$ meV) is lower that the energy scale for charge excitation. Therefore, a spin-dependent excitation is expected to have fast (charge) and slow (spin) components. Averaging over the fast dynamics may result in a (slow) quasi-steady state pure spin currents. Indeed, this have been demonstrated recently using full quantum dynamical model calculations [12]. The finding is that in a confined, unbiased, effective one-dimensional system pure coherent spin current can be generated and controlled by THz pulses if the structure contains a localized spin-orbit scatterer, similar to the Pt stripe in Fig. 1. The question to be clarified yet is whether pure spin excitation is at all useful for transmitting and storing information. The spin current as such can be generated in a versatile way, particularly in an open circuit geometry which was demonstrated by series of recent discoveries, e.g., in a spin-Seebeck effect geometry [13–16], spin-Hall effect [17], or by means of dynamic spin-pump approaches [19,18,20,21].

Previous studies evidence the influence of a diffusive spin current on a domain wall [22]. Here we attempt to address the issue of whether in principle a *pure* spin current is capable to trigger an internal dynamics/coupling within a magnetic textures (coupled DWs). To this end we proceed according to the following steps: (1) We assume that a spin current is generated, e.g., as in Ref. [12], or via spin pumping, or other means, and use the spin current carrying states (spin wave packet) as an input for the present study. (2) These states while traversing the wire scatter from the localized magnetic moments that form the DWs. This step involves the charge dynamics and is conducted quantum mechanically assuming a local (s–d) coupling of the carriers to the DW-localized moments. The calculations expose a spin-transfer torque acting on DWs upon scattering. (3) The torque results in DWs dynamics which we treat classically via LLG. (4) From the topology of the established steady, non-uniform structure of DWs we infer a local

* Corresponding author.
E-mail address: jamal.berakdar@physik.uni-halle.de (J. Berakdar).

http://dx.doi.org/10.1016/j.physleta.2014.11.033

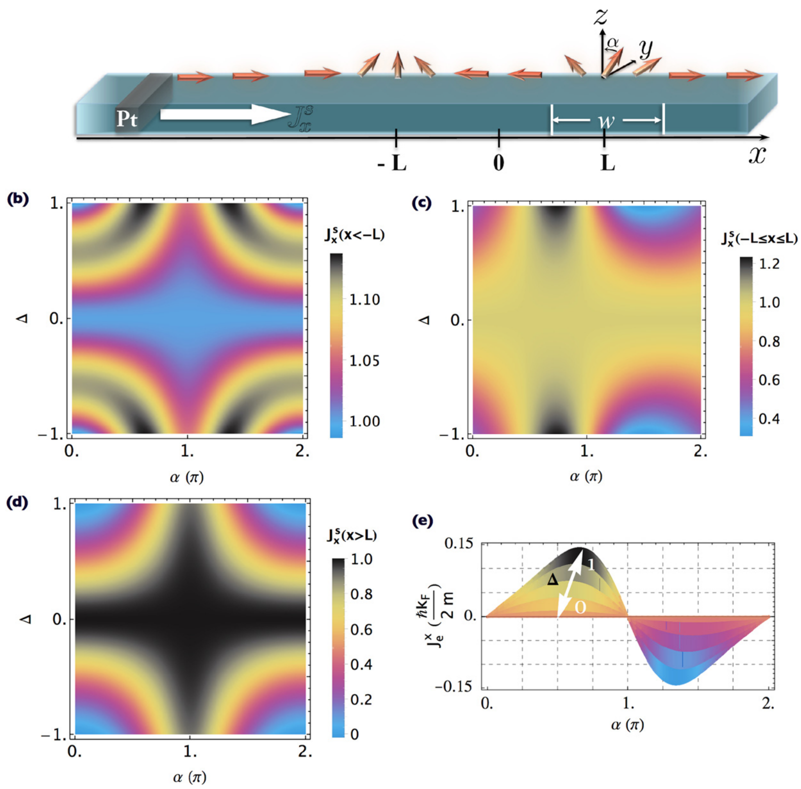

Fig. 1. A spin current J_x^s induced, e.g., by a spin pumping at a Pt stripe, scatters from localized magnetic textures in a ferromagnetic nanowire. The planar profile of the texture magnetization is shown schematically (thick arrows). The texture parameters are: the extension (w) and their relative distance ($2L$) and orientation (α) ($\alpha=\pi$ in equilibrium). (b–c) Inhomogeneous spin current in the wire. (e) The magnetic scattering induced charge current with C_2-symmetry. Δ is the effective spin-current scattering strength.

spin orbital coupling of the carriers caused, and controlled by the combined Berry phase of spin current coupled DWs.

1. Theoretical modelling

As illustrated in Fig. 1, we study an unbiased exchange-split ferromagnetic (FM) wire described by the Hamiltonian H_0. The carriers are coupled to a localized magnetic texture which forms two DWs. A spin current, $\mathbf{J}_x^s$, is triggered and traverses the wire. We are interested in the transversal dynamics of the magnetic texture.

The two DWs are assumed to have initially the same extension w and are spatially pinned by some constrictions at mutual distance $2L$ (similar to the experiment in Ref. [9]). We are mainly interested in the transversal local dynamics. The DWs profile $\mathbf{M}(x)=M_0\mathbf{n}(x)$ is parameterized by the angles $\alpha(x)$ and $\varphi(x)$, i.e., $n_x=\cos\varphi$, $n_y=\sin\alpha\sin\varphi$, and $n_z=\cos\alpha\sin\varphi$, where $\varphi(x)=\arccos[\tanh\frac{x+L}{w}]+\arccos[\tanh\frac{x-L}{w}]$. Without loss of generality, we set $\alpha(-L)=\alpha_1=0$ at the first wall and $\alpha(L)=\alpha_2=\alpha$ around the second (unless otherwise indicated, atomic units are used). Thus, $H_0=\mathbf{P}^2/2m+J\sigma_x$ that has spinor plane wave eigenstates, where m is the carriers' effective mass, $\mathbf{P}$ is the momentum operator, and J is the exchange splitting. The coupling to the (classically treated) localized moments which form the DWs can be modeled by the "s–d" Hamiltonian [10,23] $H_{sd}=g(x)\mathbf{M}(x)\cdot\boldsymbol{\sigma}$, where $g(x)$ is a local Kondo-type coupling which is active and assumed uniform in the region of the DWs. $\boldsymbol{\sigma}$ is the carrier spin vector composed from Pauli matrices $\sigma_{x,y,z}$ (we note that the localized magnetic structure (DWs) need not necessarily be part of the wire but could be a deposited magnetic structure or DWs in a adjacent or crossing wire). The change of the spectrum of the wire due to H_{sd} interaction may be calculated perturbatively (for adiabatic DW) or to all orders (for sharp DW) [24]. Here we need to go a step further because the impinging spin-current carrying wave packet $u(x,\boldsymbol{\sigma})$ is in general not an eigenstate of H_0 nor of H_0+H_{sd}, as detailed above, but it is expressible as a linear superposition of eigenstates of H_0, i.e., $u(x,\boldsymbol{\sigma})=\int dk_\sigma a_{k_\sigma}\psi_\sigma(x)$, where $\psi_\sigma(x)=\frac{1}{2}[e^{ik_\sigma x}\binom{1}{1}+e^{-ik_\sigma x}\binom{e^{i\theta}}{e^{-i\theta}}]$. The Fourier components a_{k_σ} are strongly peaked around the Fermi wave vector k_F. The expectation value of an operator $\hat{o}$ we evaluate as $\langle\hat{o}\rangle_\theta=1/(2\pi)\oint d\theta\langle\hat{o}\rangle$. The averaging over θ accounts for the residual spin precession and diffusion. The underlying mechanisms for these processes are inherent to the specific system in which the spin current is generated. An example of how such a wave packet could be accomplished is demonstrated in Refs. [12,25]. The spin-dependent transmission and reflection of $u(x,\sigma)$ from DWs occur due to the presence of the local coupling term (H_{sd}). We present below numerical results assuming a moderate carrier density of a wire for which the chemical potential is in one of the magnetically split subbands (unless otherwise stated we abbreviate $k_\sigma\equiv k$). This means, we assume a full spin polarization of the wire (described by H_0). Thus, the calculations refer to a dilute magnetic semiconductor nanowire but our goal is rather a proof of principle. The physical significance of ψ_σ and hence u becomes more clear, when evaluating the x expectation value of the associated charge-current density $\mathbf{J}^e=\langle\mathbf{j}^e(k)\rangle_\theta$ with $\mathbf{j}^e(k)=\frac{i\hbar}{2m}[(\nabla\psi_\sigma^\dagger(x))\psi_\sigma(x)-\psi_\sigma^\dagger(x)\nabla\psi_\sigma(x)]$. We find $j_x^e(k)\equiv 0$. From the spin-current density $\mathbf{j}_\mu^s(k)=\frac{i\hbar}{2m}[(\nabla\psi_\sigma^\dagger(x))\sigma_\mu\psi_\sigma(x)-\psi_\sigma^\dagger(x)\sigma_\mu\nabla\psi_\sigma(x)]$ we deduce for the spin current $J_y^s=\oint j_y^s d\theta/2\pi=0$, whereas $J_x^s=J_0^s\approx\hbar^2k_F/2m$.

2. Pure-spin-current induced torque

The primary quantity of our interest is the consequences of the spin-current transmission/reflection from DWs on the DWs-dynamics. If the internal structure of $\mathbf{M}(x)$ varies on a scale larger than the carriers wavelength at the Fermi surface, then the carrier spin follows the smoothly varying non-collinear magnetic tex-