The influence of the Rashba field on the current-induced domain wall dynamics: A full micromagnetic analysis including surface roughness and thermal effects

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FW-15

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1. Introduction - Motivation

- Understanding the **Domain Wall (DW) dynamics** under in-plane Spin Polarized Currents along thin ferromagnetic strips with high Perpendicular Magnetocristalline Anisotropy (PMA) sandwiched between to dissimilar non-magnetic layers (Pt/Co/AlO).

- Experiments have pointed out an important **enhancement of the nonadiabaticity** ($\xi \approx 1$) and the **occurrence of a transversal Rashba field $\boldsymbol{H}_R$** responsible of the rigid DW propagation

- Technological relevance due to **low current operation with negligible Joule heating and high rigid DW mobility with very high velocity**.

- The origin of the Rashba field $\boldsymbol{H}_R$ is the **Spin-Orbit Interaction** (SOI) on the conduction electrons which originates from the **Structural Inversion Asymmetry** (SIA).

$$\boldsymbol{H}_R = \frac{\alpha_R |e| P}{\mu_0 \mu_B M_s}\left(\boldsymbol{j}_{app} \times \boldsymbol{u}_z\right) = \frac{\alpha_R |e| P}{\mu_0 \mu_B M_s} j_a \boldsymbol{u}_y$$

2. Experimental background

I. M. Miron et al. Nature 10, 419, (2011)

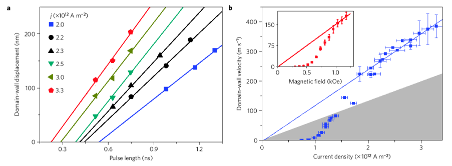
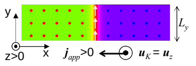
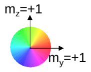


Figure 3 | Domain-wall velocity induced by current or field in the PtCoAlO$_x$ layers. a, Current-induced domain-wall displacement as a function of pulse length, for current densities j ranging from 2.0 to 3.3×10^{12} A m^{-2}. Each data point is an average over more than 10^3 individual displacements. Error bars calculated as the standard error of the average value are smaller than the data points. **b**, Domain-wall velocity as a function of the current density. Vertical error bars are calculated as the error of the linear regression. Horizontal error bars are important only for the shortest pulses where the plateau of constant current is reduced. They are caused by the imprecision in the determination of the pulse height. The solid line is a linear fit to the domain-wall flow regime (occurring for $j > 1.8 \times 10^{12}$ A m^{-2}). The shaded area maps the region where the velocity values are compatible with the turbulent motion. The inset shows a measurement of the domain-wall velocity as a function of the magnetic field. When $H > 1.0$ kOe, the domain-wall mobility saturates (indicated by the red solid line) and thus demonstrates a similar behaviour to the current-induced velocity.

3a. Numerical Details

3.1 Geometry: Cross-section: $L_y x L_z$=120x3nm^2





Cell size $\Delta x = 3\text{nm}$

Infinite strip: Moving computational region

3.2 Material parameters:

$$\begin{cases} M_s = 3\times10^5\,\text{A/m} \\ A = 1.0\times10^{-11}\,\text{J/m} \\ K_1 = 2\times10^5\,\text{J/m}^3 \end{cases} \qquad \begin{cases} l_{exch} = \sqrt{\dfrac{2A}{\mu_0 M_s^2}} = 3\text{nm} \\ \delta = \sqrt{\dfrac{A}{K_1}} = 7\text{nm} \end{cases} \qquad \begin{matrix} \alpha = 0.2 \\ P = 0.5 \\ \xi = 0.4 \end{matrix}$$

Rashba parameter: $\alpha_R = 10^{-11}\text{eVm}$

3b. Dynamics

Landau-Lifshitz-Gilbert + in-plane STT: $b_J = \dfrac{\mu_B P}{e M_s} j_a$

$$\frac{d\boldsymbol{M}}{dt} = \overbrace{-\gamma_0 \boldsymbol{M}\times\left(\boldsymbol{H}_{eff}+\boldsymbol{H}_{th}\right)}^{\text{precession}} + \overbrace{\frac{\alpha}{M_s}\boldsymbol{M}\times\frac{d\boldsymbol{M}}{dt}}^{\text{dissipation}} + \overbrace{\underbrace{b_J\left(\boldsymbol{u}_x\cdot\nabla\right)\boldsymbol{M}}_{\text{adiabatic}} - \underbrace{\xi\frac{b_J}{M_s}\boldsymbol{M}\times\left(\boldsymbol{u}_x\cdot\nabla\right)\boldsymbol{M}}_{\text{non-adiabatic}}}^{\text{In-plane Spin Transfer Torque}}$$

Effective field: $\boldsymbol{H}_{eff} = \boldsymbol{H}_{exch} + \boldsymbol{H}_{dmg} + \boldsymbol{H}_{ani} + \boldsymbol{H}_R$ →

Rashba field

$$\boldsymbol{H}_R = \frac{\alpha_R |e| P}{\mu_0 \mu_B M_s}\left(\boldsymbol{j}_{app}\times\boldsymbol{u}_z\right)$$

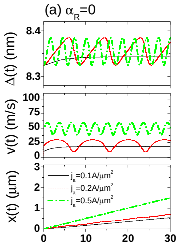
$$\alpha_R = 10^{-11}\text{eVm}$$

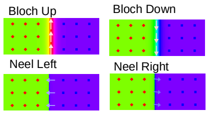
Thermal field:

$$\left\langle \boldsymbol{H}_{th,i}(\boldsymbol{r},t)\right\rangle = 0$$

$$\left\langle \boldsymbol{H}_{th,i}(\boldsymbol{r},t)\boldsymbol{H}_{th,j}(\boldsymbol{r}',t')\right\rangle = \frac{2\alpha K_B T}{\gamma_0 \mu_0 M_s}\delta_{ij}\delta(\boldsymbol{r}-\boldsymbol{r}')\delta(t-t')$$

4a. Results: Perfect strips at T=0 In the **absence** of Rashba field



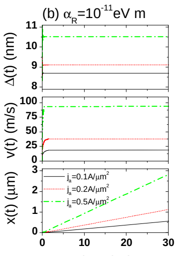


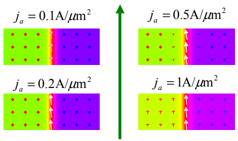
$j_W = 0.12\text{A}/\mu\text{m}^2$

There is a **Walker breakdown** current j_W:

- j_a<j_W: Rigid DW propagation
- j$_a$>j_W: Turbulent DW propagation

4b. Results: Perfect strips at T=0 In the **presence** of Rashba field



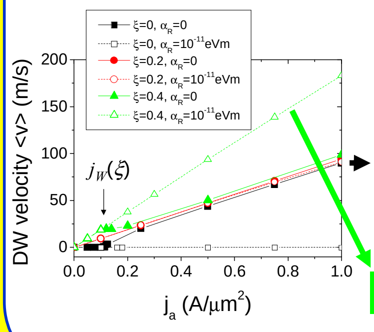


$$\boxed{\boldsymbol{H}_R = \frac{\alpha_R |e| P}{\mu_0 \mu_B M_s}\left(\boldsymbol{j}_{app}\times\boldsymbol{u}_z\right) = \frac{\alpha_R |e| P}{\mu_0 \mu_B M_s} j_a \boldsymbol{u}_y}$$

There is **NOT Walker breakdown** current

The DW propagates rigidly due to the transverse Rashba field

4c. Results: Perfect strips at T=0 **DW mobility** $\boxed{m = \frac{dv}{dj_a}}$



In the absence of SOI ($\boldsymbol{H}_R$ =0):

- Rigid DW propagation (j_a<j_W):

$$m_R(\xi) = \begin{cases} 0 & \xi = 0 \\ \dfrac{\xi}{\alpha}\dfrac{\mu_B P}{eM} & \xi \neq 0 \end{cases}$$

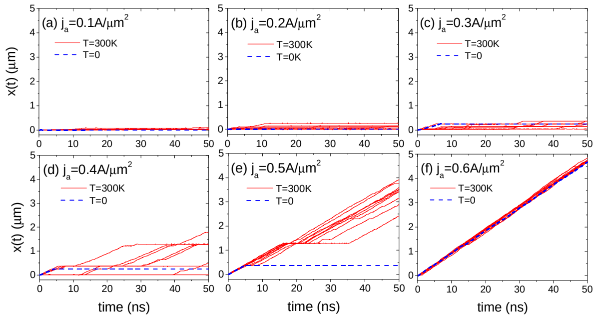
- Turbulent DW propagation (j_a>j_W):

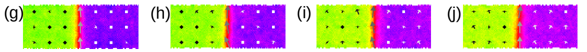
$$m_T(\xi) = \frac{1+\alpha\xi}{1+\alpha^2}\frac{\mu_B P}{eM} \xrightarrow[\substack{j_a >> j_W \\ \alpha\approx\xi<<1}]{} \frac{\mu_B P}{eM}$$

The DW propagates rigidly due to the transverse Rashba field ($\boldsymbol{H}_R$ ≠0) with

$$\boxed{m_R(\xi) = \frac{\xi}{\alpha}\frac{\mu_B P}{eM}}$$

5a. Strips with Surface Roughness

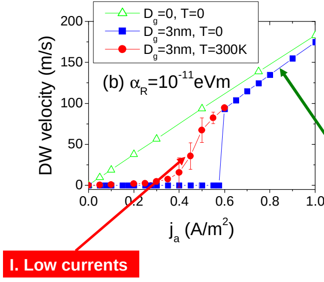




$j_a = 0.1\text{A}/\mu\text{m}^2$ $j_a = 0.3\text{A}/\mu\text{m}^2$ $j_a = 0.6\text{A}/\mu\text{m}^2$ $j_a = 0.75\text{A}/\mu\text{m}^2$

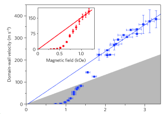
5b. Strips with Surface Roughness

MODELING E. Martinez. JAP (2011)



EXPERIMENT

I. M. Miron et al, Nature 10, 419, (2011)



I. Low currents

- Creep regime: Disorder and Thermal effects
- [<v>] increases exponentially with j$_a$

$$\boxed{[<v>] = v_0 \exp\left[\frac{E_b(j_a)}{K_B T}\right]}$$

II. High current

- High current Rigid regime: Rashba
- The [<v>] increases linearly with j$_a$

$$\boxed{[<v>] = \frac{\xi}{\alpha}\frac{\mu_B P}{eM} j_a}$$

6. Conclusions

- The Spin-Orbit Interaction (SOI) in Structures with Inversion Asymmetry (SIA) induces a transverse Rashba field $\boldsymbol{H}_R$ which is perpendicular to both $\boldsymbol{u}_z$ and $\boldsymbol{j}_{app}$, and **extends the Rigid Regime** towards higher currents **avoiding the Walker breakdown**.

- Great potential for applications: **High DW velocity under very low current with negligible Joule heating effect**.

- **Realistic micromagnetic simulations** of the DW velocity vs current, including both the effect of **Surface Roughness** and **Thermal fluctuations**, are in good agreement with recent experimental observations.

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Wednesday, 2 Nov, 2011
SAGUARO BALLROOM, 1:00 - 5:00