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Efficient stopping of current-driven domain wall using a local Rashba field

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Fully electric operated magnetic memories are promising for fast and high-density memories. Switching of the magnetization of a thin ferromagnetic layer by applying an electric current has been accomplished using the spin-transfer effect.\(^1,2\) Driving a ferromagnetic domain wall by current pulse has also been achieved. Most in-plane magnetic anisotropy systems are in the extrinsic pinning regime, where the wall motion is driven by a non-adiabatic torque,\(^3,4\) while the spin-transfer torque in the intrinsic pinning regime\(^5\) has been reported in perpendicular magnetization material.\(^6\) Recently, several possibilities for using multilayers for fast domain wall motion have been proposed.\(^7-10\) For ultrahigh density memories, the use of a sequence of domain walls on a patterned wire (“race track”) controlled by an electric current, called a racetrack memory, has been proposed.\(^11\) For memory applications of such multi-domain wall devices, techniques to stop a moving wall at an intended position precisely and without delay is essential. An artificial pinning site has been proposed for stopping the wall;\(^12\) however, efficient and reliable stopping is difficult because of the difficulty in fabricating well-controlled and uniform pinning centers. Moreover, fast stopping requires a strong pinning potential, which necessitates a large current density for depinning.

In this paper, we propose a highly efficient and reliable mechanism to stop a moving domain wall using a locally embedded Rashba spin–orbit interaction. The Rashba interaction generates a strong effective magnetic field when an electric current is injected.\(^13,14\) This effective field leads to strong pinning of a moving wall at the Rashba region if the applied current density is below the capturing threshold \(j_{\text{cap}}\). Moving the wall from the pinning center is performed by applying a high current pulse above the depinning threshold \(j_{\text{dep}}\). Rashba pinning is highly reliable because introducing a Rashba interaction by attaching a small thin layer of heavy metals in a controlled manner is easy to implement with the present technology. The present mechanism also has the advantage of lower energy consumption compared with geometrical pinning. The fact that the capturing threshold \(j_{\text{cap}}\) is lower than \(j_{\text{dep}}\) indicates that the energy required to shift the wall positions over a distance of multiple pinning sites is much lower than that of the geometrical pinning mechanism.

The system we consider to demonstrate the Rashba pinning effect is simple; it includes a ferromagnetic wire with the Rashba interaction locally embedded by attaching a small thin film of heavy metals [Fig. 1(a)]. The Rashba field, represented by the vector \(\alpha_R\), is perpendicular to the wire plane. The current applied along the wire generates an in-plane effective magnetic field orthogonal to the wire. The \(z\)-axis is selected along \(\alpha_R\), while the \(x\)-axis is selected along the wire. The wall we consider is a Bloch wall, with the magnetic easy axis along the \(z\)-direction and the wall plane at equilibrium lying in the \(yz\)-plane. The wall structure is stabilized by the current when the wall is in the Rashba region because of the generated magnetic field along the \(y\)-direction. The Hamiltonian of the localized spin \(S\) is given by

\[
H = \int d^3r \left[ \frac{J}{2} (\nabla S)^2 - \frac{K}{2} (S_z)^2 + \frac{K_1}{2} (S_y)^2 + E_{R,S} \right].
\]

where \(J, K, K_1, a\) are the exchange energy, easy and hard axis anisotropy energies, and the lattice constant, respectively. The last term \(E_{R,S}\) describes the influence of the

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**Fig. 1.** (a) Setting of the system. A domain wall in a ferromagnetic wire along the \(x\)-axis is driven by a steady current \(j\) along the \(-x\)-direction. The Rashba interaction, represented by the vector \(\alpha_R\), is embedded in the shaded region near \(x = 0\). From symmetry, \(\alpha_R\) is along the \(z\)-axis (perpendicular to the wire) and produces a local strong effective magnetic field along the \(-y\)-direction when a current is applied. (b) Plots of \(f(X)\) and \(f'(X)\), which represent the profiles of the pinning torque and force, respectively, for \(\lambda = 1\) and \(\Lambda = 1\).
effective magnetic field due to the Rashba interaction. The wall configuration centered at \(x = X\) is represented by\(^{15}\)

\[
S_x = \frac{S \cos \phi}{\cosh \frac{x - X}{\lambda}},
\]

\[
S_y = \frac{S \sin \phi}{\cosh \frac{x - X}{\lambda}},
\]

\[
S_z = S \tanh \frac{x - X}{\lambda},
\]

where \(\lambda = \sqrt{J/K}\) is the width of the wall, \(\phi\) is the angle of the wall plane, and \(S\) is the magnitude of the localized spin. The Rashba interaction embedded in the region \(-\Lambda/2 < x < \Lambda/2\) is represented by the Hamiltonian

\[
H_R = -\frac{1}{\hbar} \mathbf{p} \cdot (\mathbf{\sigma} \times \mathbf{a}_R) \theta_R(x),
\]

where \(\mathbf{p}\) is the electron’s momentum, \(\mathbf{a}\) is a vector of Pauli matrices, and \(\theta_R(x) \equiv (1 - \theta(\Lambda/2))\theta(-\Lambda/2)\), where \(\theta(x) = 1\) for \(x \geq 0\) and \(\theta(x) = 0\) for \(x < 0\). We assume that the Rashba field is applied homogeneously in the region \(-\Lambda/2 < x < \Lambda/2\). When the current density \(j\) is applied to the wire, the conduction electron spin in the Rashba region experiences a magnetic field \(B_R = \frac{ma^3}{\hbar^2} \mathbf{a}_R \times \mathbf{j}\), where \(m\) is the electron mass, \(e\) \((< 0)\) is the electron charge, and \(\gamma \equiv |e/m|\) is the gyromagnetic ratio. In the case of a strong \(sd\) exchange interaction between the localized and electron spins (adiabatic limit), the field acting on the localized spins is \(B_R\) but with \(j\) replaced by spin current \(j_s \equiv Pj\), namely

\[
B_R = -B_R \theta_R(x) \hat{y},
\]

where \(\hat{y}\) is the unit vector along the \(y\)-axis and \(B_R \equiv \frac{ma^3}{\hbar^2} \mathbf{a}_R \times \mathbf{j}\), where positive \(j\) is chosen along the \(-x\)-direction. In addition to the field \(B_R\), it was theoretically pointed out that the Rashba interaction induces an effective magnetic field along the direction \(B_R \times \mathbf{n}\), where \(\mathbf{n}\) denotes the localized spin direction.\(^{16,17}\) This field, a perpendicular field, turned out to be smaller than \(B_R\) by a factor of 0.01–0.2 in dirty metals.\(^{16}\) Moreover, the perpendicular field does not affect much the pinning effect due to \(B_R\) in the present case, as the larger field \(B_R\) tends to pin the wall by pointing \(\mathbf{n}\) inside the wall along \(B_R\), resulting in small \(B_R \times \mathbf{n}\). Thus, in the following calculation, we neglect the effect of the perpendicular effective field and focus on the dominant pinning effect by the field \(B_R\).

The additional energy of the wall arising from the Rashba-induced field \(B_R\) is given by

\[
E_{R,S} = \frac{N_w ma^3}{2e\hbar} \alpha_R j_R f(X) \sin \phi,
\]

where \(A\) is the cross section of the wire, \(N_w = \frac{2\lambda A}{\pi}\) is the number of spins in the wall, and

\[
f(X) \equiv \int_{\frac{X}{\lambda}}^{\frac{X}{\lambda}} \frac{dz}{\cosh \frac{z}{\lambda}} = 2 \left[ \tan^{-1} \left( \frac{\Lambda/2 - X}{\lambda} \right) - \tan^{-1} \left( -\frac{\Lambda/2}{\lambda} \right) \right].
\]

The force on the wall due to the Rashba field is given by

\[
\frac{\delta E_R}{\delta X} = \frac{N_w ma^3}{2e\hbar} \alpha_R j_R \lambda f'(X) \sin \phi
\]

\[
\lambda f'(X) = \frac{1}{\cosh \left( \frac{\Lambda/2 + X}{\lambda} \right)} - \frac{1}{\cosh \left( \frac{\Lambda/2 - X}{\lambda} \right)}.
\]

The behaviors of the functions \(f\) and \(f'\) are plotted in Fig. 1(b). Including Gilbert damping \(\alpha\) and the \(\beta\) (nonadiabaticity) term, the equation of motions for the wall are\(^{15}\)

\[
\phi + \frac{\Lambda}{\lambda} \frac{X}{\lambda} = Pj \left[ \frac{\beta}{2} - \alpha_R \dot{f}'(X) \sin \phi \right]
\]

\[
\dot{X} - a X = -v_c \sin 2 \phi + Pj \left[ 1 + \alpha_R f(X) \cos \phi \right].
\]

Here,

\[
v_c \equiv \frac{K_1 \lambda S}{2\hbar}, \quad \alpha_R \equiv \frac{ma^3}{\hbar^2} \alpha_R, \quad j \equiv \frac{a^3}{2e\hbar^2} j.
\]

As \(e < 0\), \(j\) is opposite to \(j\), and the wall moves toward the direction of \(j\). For positive \(j\), the wall favors the configuration \(\phi \approx -\pi/2\) because of the Rashba effect.

Typical solutions of the equation of motions are shown in Fig. 2. Figure 2(a) shows the capturing dynamics of the wall under a current driven from the initial position outside the Rashba regime \((X/\lambda = -5)\). We found that there is a
threshold current density $j_{\text{cap}}$ below which the wall is captured by the Rashba pinning region. The capturing threshold is plotted as a function of $\alpha_R$ in Fig. 3 and is an order of magnitude lower than the intrinsic pinning threshold $j_1 = v_c/P^{(15)}$ if $\alpha_R \gtrsim O(1)$. An important observation here is that the Rashba field blocks the wall motion with a realistic current value of $j \lesssim O(1)$ if $\alpha_R$ is of the order of unity, which corresponds to a rather weak value of $\alpha_R = 0.01 \text{ eV Å}$; thus, the weak Rashba interaction is enough for practical devices.

The capturing threshold depends on $\beta$ since the wall speed when it enters the Rashba region depends on $\beta$.

We now analyze the pinning mechanism. We focus on the wall configuration near $X \sim 0$ and $\phi = -\pi/2$ and write $f'(X) \approx -f_1 X/\lambda^2$. The equilibrium pinned configuration at finite $j$ is then given by

$$X_{\text{pin}} = \frac{\beta \lambda}{f_1\alpha_R}$$

$$\delta \phi_{\text{pin}} = \phi_{\text{pin}} + \frac{\pi}{2} = -\frac{j}{2v_c/P + f_0\alpha_R},$$

where $f_0 \equiv f(0)$. Since $\beta \ll 1$, notice that the captured position of the wall is very close to the center of the Rashba region as far as $\alpha_R \gtrsim O(1)$. Deviation of the angle, $\delta \phi$, is small only when either $j \ll 1$ or $j \gg \frac{\alpha_R}{v_c}$ or $f_0$. The equilibrium pinned configuration obtained from Eq. (8) is plotted in Fig. 4. Note that $\phi_{\text{pin}}$ is insensitive to $\beta$ in contrast to $X_{\text{pin}}$.

When the deviation $\delta \phi_{\text{pin}}$ is not small, the wall moves backward when the current is stopped. In fact, the wall speed and the wall configuration near $X = -\frac{j}{2\lambda}$, which means that the wall moves over a substantial distance of $\delta X = -\frac{\delta \phi_{\text{pin}}}{\lambda}$ when the phase $\phi$ reduces to the equilibrium value of $-\pi/2$ at $j = 0$. In reality, this is not be serious for devices since the backward motion is removed simply by the use of a smooth cut of the current, as is understood from Fig. 4.

To see the capturing dynamics, we expand the motion equation with respect to $X$ and $\delta \phi$. Neglecting small quantities of the order of $\alpha^2$ and $\alpha \beta$, we obtain

$$X = Pj + \delta \phi (2v_c + P_0\alpha_R) - \alpha \alpha_R f_1 P j^2 X^2,$$

$$\lambda \delta \phi = Pj (\beta - \alpha) - \alpha \alpha_R f_1 P j^2 X^2.$$  

The second equation indicates that when the wall enters the region of $X > 0$ from the $X < 0$ region, $\delta \phi$ becomes negative because $\delta \phi \approx -\alpha_R f_1 P j^2 X^2 < 0$, resulting in a slow down of the wall because of the first equation. The wall is captured if this deceleration is strong for an initial wall velocity proportional to $j$. The correlation between $X$ and $\delta \phi$ is clearly seen when $j = 0.32$ in Fig. 2(a).

The time needed for capturing the wall, $\tau_{\text{cap}}$, is an important parameter for devices. It is estimated based on the linearized equations that Eq. (11) reduces to the second-order differential equation

$$\delta \phi + \frac{\alpha}{\lambda} \left[2v_c + \frac{j}{\lambda} \alpha_R P j + \frac{f_1}{\alpha_R} \alpha_R P j \right] [2v_c + f_0 \alpha_R P j] = -\frac{j}{\lambda} \alpha_R (P j)^2,$$

where $\lambda \equiv \frac{1}{2} (f_0 + f_1)$. The time for capturing is given by the imaginary part of the angular frequency $\omega$ of the solution, $\delta \phi \propto e^{-i\omega t}$, specifically,

$$\tau_{\text{cap}} = \frac{1}{\Im \omega} = \alpha \frac{\lambda}{v_c} \left(1 + \frac{P f_0}{v_c} \alpha_R \right)^{-1}.$$  

We choose the hard-axis energy as $K_{\perp} \sim 8 \times 10^{-26} \text{ J per site}$, which is reasonable in perpendicular media such as CoNi.\textsuperscript{6} The wall thickness is reported to be less than 10 nm. Choosing $\lambda = 5 \text{ nm}$, the intrinsic pinning threshold, $j_i \equiv \frac{26}{v_c K_{\perp}} K_{\perp} \lambda^2$ is of the order of $10^{-3} \text{ A/m}$, which is consistent with experimental results.\textsuperscript{6} In this case, $v_c$ is approximately 2 m/s, and the capturing time is $\tau_{\text{cap}} = 250 \text{ ns}$ if $\alpha = 0.01$ and if $\frac{1}{\lambda} \alpha_R \ll 1$. Since this seems rather slow, systems having either larger $K_{\perp}$ or a larger Gilbert damping parameter $\alpha$ are favorable for fast devices. Extrinsic enhancement of the Gilbert damping parameter, as proposed in Ref. 18 may also be useful.

We have seen that stopping the wall at the Rashba pinning potential is realized by applying a current density below $j_{\text{cap}}$. To set the wall in motion again by applying a new current pulse, there is another threshold value for depinning since a pinning potential is generated as soon as the current is injected. The depinning threshold current density is calculated numerically by considering the initial condition of $X = 0$ and $\phi = -\pi/2$. The wall dynamics is shown in Fig. 2(b), and the depinning threshold is plotted in Fig. 3. Notice that $j_{\text{dep}}/v_c$ is larger than unity for $\alpha_R \gtrsim 0.6$, but decreases for small $\alpha_R$. For device operations, two distinct values of the current density, one lower than $j_{\text{cap}}$ and the other larger than $j_{\text{dep}}$, are used for

![Fig. 3.](image-url)  

![Fig. 4.](image-url)
moving and stopping the wall at an intended position. Materials with $\alpha_R \lesssim 1 \lesssim C_11 R \lesssim 1$ are suitable for such operations. To shift the wall position, the initial magnitude of the pulse must be larger than $j_{\text{dep}}$, but the required current to overcome unnecessary pinning sites is lower than $j_{\text{cap}}$ (and above $j_{\text{cap}}$). The current must vanish smoothly at the intended pinning site to avoid backward motion.

The results we have found are striking since they show that even a weak Rashba interaction of the order of $\alpha_R = 0.01 \text{ eV Å}$ is sufficient for stopping the wall when locally introduced. Instead, a strong Rashba interaction like $\alpha_R = 3 \text{ eV Å}$ as realized on Bi/Ag is then approximately 300, and the wall is too strongly pinned. From this aspect, we believe there are many candidate systems for the present Rashba pinning device. Our discovery is expected to be useful for realizing domain wall-based shift memories such as racetrack memory (Fig. 5).

Our results also suggest that heavy atom impurities may cause strong pinning by modifying in-plane magnetic anisotropy energy as a result of the Rashba-induced magnetic field. This possibility seems consistent with the fact that the extrinsic pinning effect is dominant in in-plane, easy axis anisotropy materials.

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**Note added in proof**—We found that domain wall pinning by attaching antiferromagnets was experimentally studied by Polencic et al. [Appl. Phys. Lett. 105, 162406 (2014)].

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Fig. 5. Schematic showing a shift memory operation based on the Rashba pinning effect. The top configuration corresponds to the information 10100, where 1 and 0 correspond to the pinning site (shown by shaded areas) with and without a domain wall (shown by black). Shifting the wall position to the bottom configuration indicates 00101 is carried out by a current pulse with average amplitude smaller than the depinning threshold (but above $j_{\text{cap}}$).