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Bistable perpendicular switching with in-plane spin polarization and without external fields

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ABSTRACT

To-date, all experiments switching perpendicular magnetic anisotropy (PMA) materials with in-plane spin polarization require external *B*-fields. Here, in two approaches, it is shown that with Rashba-type in-plane spin polarization and PMA, bistable switching is achievable without external *B*-fields, and at currents on the order of 10^7 A/cm^2, consistent with recent experiments. Utilization of PMA is primarily discussed, demonstrating the potential for two possibilities: (1) in-plane polarization as a 'natural' candidate for precessional switching and (2) bistable switching using a tilted anisotropy axis. Both are shown to lead to stable perpendicular switching without an external *B*-field, even though spin polarization is in-plane.

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Research in spintronics has given rise to a range of relevant technological applications including spintronics-based transistors, random access memory (RAM), *rf*-nano-oscillators for mobile applications, and logic devices [1,2]. In the case of RAM, a promising candidate is spin-transfer torque magnetic random access memory (STT-MRAM). As a contender with DRAM, ideally, a notable advantage is that it is nonvolatile, owing to the use of magnetic layers to store the bit (rather than storing leaky-charge). This difference, alone, leads to significantly lower power consumption, enabled by the use of spin current to manipulate localized electron spins. In systems such as STT-MRAM, there is a need to polarize itinerant electron spins to enable transferring torque to the free layer. However, as better understood now, the spin polarization process may be done in more than one way, and this point may lead to ways to further improve MRAM device performance, as well as other devices.

The most common way to polarize itinerant electrons in STT-MRAM devices, anticipated by Slonczewski and Berger, is to pass the spin current through a uniformly magnetized metallic layer before (or after) entering the magnetic free layer whose magnetic state is to be controlled [3,4]. In this scheme, demonstrations of optimized conventional STT-MRAM switching in devices have achieved current densities $\sim 10^6$ A/cm^2 with current perpendicular to plane (CPP). For memory cells using transistors, the total current needed to switch the magnetic state of the device is a limiting factor for realizing on-chip operation and should be as low as possible. One reason, among others, is to allow for smaller transistors which support higher capacity. Moreover, because MRAM devices currently demonstrating the strongest signal use MgO barriers, a potential concern is the life of the device as the write voltage is applied repeatedly [5], which may lead to electrical fatigue and thus premature failure. One way to avoid this is by using alternative polarization techniques that do not require higher voltages across the MgO barrier, yet still provide enough torque to switch the magnetic data storage layer. Spin–orbit interaction (SOI)-based polarization offers this possibility.

SOI, explored earlier in semiconductors, and very recently in metallic systems, provide a distinct spin polarization mechanism compared to the process using a magnetic layer [6,7]. It is purely electrical in nature, and leads to additional favorable attributes such as symmetrical switching and lower total current, for comparable current densities. One form of SOI, whose Hamiltonian is linear in the wave vector **k**, is known as Rashba and it has also been linked to phenomena such as spin Hall effect and strain-induced spin polarization [8–11]. Rashba spin torque was theoretically predicted by several groups, independently, including Tan et al., Obata et al., and Manchon et al., in ferromagnetic materials. It has been demonstrated recently for applications controlling bistable states of a cobalt layer [11–15]. However, in these demonstrated cases, an external *B*-field is needed to observe bistable

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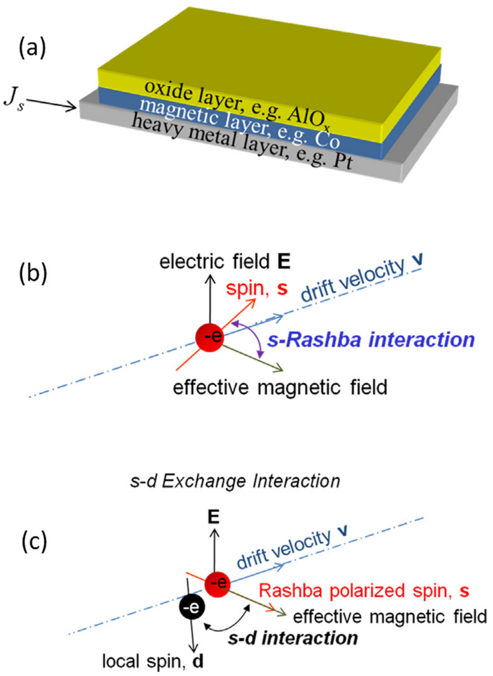

Fig. 1. (a) Example of a Rashba configuration injecting current into the heavy metal layer. The two interfaces of the magnetic layer give rise to Rashba polarization of spins. (b) Illustration of Rashba polarization with SOI and (c) s–d exchange interaction which mediates Rashba polarization to transfer torque to the magnetic layer.

switching in materials with PMA and in-plane polarization. This may be undesirable at the device level, requiring materials to deliver this field.

This work focuses in the direction towards investigating potential ways to avoid this field. Specifically, aspects of the dynamics and switching behavior of metallic magnetic layers driven by in-plane spin polarization such as Rashba are discussed, considering precessional switching and also using in-plane spin polarization together with a tilted anisotropy axis. In the case of Rashba, the average polarization lies mostly in the plane of the film and can be expressed as an effective magnetic field given by [11–14]

$$\mathbf{H}_R = \frac{\alpha_R m_e J_s}{\hbar e \mu_0 M_s} \vec{\mathbf{e}}_E \times \vec{\mathbf{e}}_{J_s} = H_R \vec{\mathbf{e}}_E \times \vec{\mathbf{e}}_{J_s} \tag{1}$$

α_R is the so-called Rashba constant; m_e is the electron mass; J_s is the source charge current density; $\vec{\mathbf{e}}_E$ is the unit vector along the direction of the interfacial electric field needed for Rashba polarization; $\vec{\mathbf{e}}_{J_s}$ is the unit vector along the direction of J_s; $\hbar$ is Planck's constant divided by 2π; e is the electron charge strength; μ_0 is the permeability of free space; M_s is the saturation magnetization of the magnetic layer. H_R is therefore the strength of the Rashba field. The direction of the effective Rashba field in (1) is thus determined by the current direction and interfacial surface normal.

Fig. 1 illustrates an in-plane spin polarization device structure typical of recent experiments [15,16]. Simplified illustrations of the physical processes that take place are also shown, consisting of Rashba polarization by SOI and s–d exchange, which mediates the interaction between the Rashba polarization and the local moments.

The structure in Fig. 1 consists of three layers: one magnetic layer between two nonmagnetic layers. The nonmagnetic layers consist of a heavy metal layer and typically an oxide layer [15,16]. For the results discussed, most parameters used in this analysis are taken from reported estimates from experiments on a realized device (and listed in Table 1).

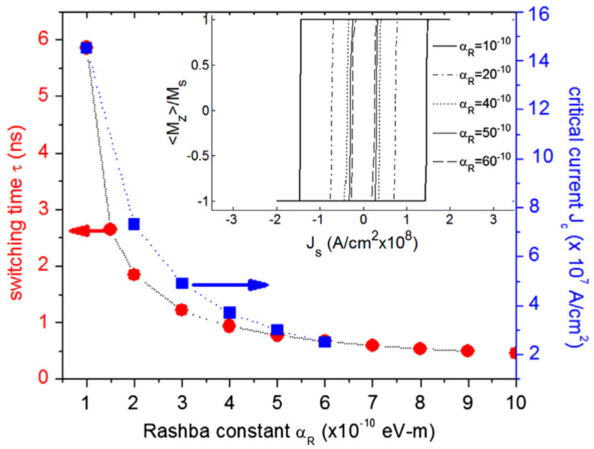

Fig. 2. Simulated switching times versus Rashba parameter α_R and simulated critical currents from hysteresis loops for a 65 nm size, 0.6 nm thick layer switching with in-plane Rashba polarization and in-plane anisotropy. Inset shows hysteresis curves generated for critical current computation.

To consider the magnetization dynamics, the Landau–Lifshitz–Gilbert (LLG) equation is solved, given by [17]

$$\frac{\partial \mathbf{M}}{\partial t} = -\gamma' \mathbf{M} \times \mathbf{H}_T - \frac{\gamma' \alpha}{M_s} \mathbf{M} \times \mathbf{M} \times \mathbf{H}_T \tag{2}$$

$\mathbf{M}$ is the local magnetization; $\gamma' = \gamma / 1 + \alpha^2$; α is the dimensionless Gilbert damping constant, not to be confused with the Rashba constant α_R; M_s is the saturation magnetization where $|\mathbf{M}| = M_s$; $\mathbf{H}_T$ is the total effective magnetic field, which includes the Rashba field $\mathbf{H}_R$, crystalline anisotropy, magnetostatic, exchange, as well as the magnetic field due to the charge current, i.e. the Oersted field.

For computing the switching time τ and critical switching currents J_c via dynamic hysteresis loops, the case with both in-plane spin polarization and magnetic anisotropy is considered. The computed switching times and hysteresis curves as functions of α_R are shown in Fig. 2.

The switching times decrease more exponentially with increasing α_R, while the critical current actually reduces inversely. The inverse behavior of J_c is evidenced in our observation that $J_c \cdot \alpha_R$ is constant. The results suggest that at comparable STT-MRAM current densities, Rashba polarization may also lead to switching a magnetic layer. For a 0.6 nm film and a device size of 65 nm, a total current of 65 µA is needed. Considering that the parameters used here are not optimized, these values may likely be reduced further.

Perpendicular anisotropy is a more energetically favorable option to consider for thin films (i.e. lower J_c) [18]. Recently, in-plane charge currents and spin polarization have been shown to be able to control bistable perpendicular switching, superimposing an external magnetic field to induce perpendicular Rashba polarization [16,18,19]. Similar conditions are found when spin Hall drives the magnetic layer. Two alternative options for switching magnetic layers with PMA are discussed here that have the advantage that they do not require an external B-field to enable bistable perpendicular switching. Thus, a simpler device configuration and smaller 'footprint' should be possible. The first of these considers the fact that with in-plane polarization and perpendicular anisotropy, a natural way to achieve precessional switching is provided. Precessional switching arises here because of the polarization field being in the plane of the film, while the magnetization aligns with a perpendicular anisotropy axis. The magnetization will initially precess about the in-plane polarization field, passing through the '−1' state several times in completing many precessional rounds before aligning with the Rashba field. Consequently, controlling the timing of when the current pulse is turned off is needed to achieve

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