Spin-orbit torque switching without external field with a ferromagnetic exchange-biased coupling layer

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Magnetization reversal of a perpendicular ferromagnetic free layer by spin-orbit torque (SOT) is an attractive alternative to spin-transfer torque (STT) switching in magnetic random-access memory (MRAM) where the write process involves passing a high current across an ultrathin tunnel barrier. A small symmetry-breaking bias field is usually needed for deterministic SOT switching but it is impractical to generate the field externally for spintronic applications. Here, we demonstrate robust zero-field SOT switching of a perpendicular CoFe free layer where the symmetry is broken by magnetic coupling to a second in-plane exchange-biased CoFe layer via a nonmagnetic Ru spacer. The preferred magnetic state of the free layer is determined by the current polarity and the nature of the interlayer exchange coupling (IEC). Our strategy offers a scalable solution to realize bias-field-free SOT switching that can lead to a generation of SOT-based devices, that combine high storage density and endurance with potentially low power consumption.

For memory applications, a storage layer with perpendicular magnetic anisotropy (PMA) is preferred because it offers higher storage density, better thermal stability and lower power consumption than a layer with easy plane anisotropy. However, deterministic SOT switching of a perpendicularly magnetized nanomagnet usually relies on an external magnetic field to break the symmetry. SOT switching without an external field has recently been demonstrated in systems with lateral asymmetry or with tilted magnetic anisotropy but neither of these schemes is easily scalable.

Here, we combine two concepts that have been developed in the context of modern hard-disc read heads and magnetic tunnel junctions: exchange bias and exchange coupling across a thin spacer to achieve scalable SOT switching without an external field. Using a stack based on a perpendicularly-magnetized CoFe free layer sandwiched between a Pt underlayer and a Ru overlayer, we show that the free layer can be deterministically switched by SOT from the Pt. The symmetry-breaking issue is resolved by exchange coupling the free layer, via a Ru spacer, to an in-plane exchange biased CoFe pinned layer.

Our stacks, illustrated in Figure 1(a), consist of Ta(1)/Pt(5)/CoFe(0.8)/Ru(tRu)/CoFe(1.5)/IrMn(10)/Pt(2) (thicknesses in nanometre). The Ru has been selected for the spacer because it provides the strongest IEC and together with the Pt underlayer, it improves the PMA of the CoFe free layer. A series of control samples with varying Pt thickness: Si/SiO2(substrate)//Ta(1)/Pt(tPt)/CoFe(0.8)/Ru(3) were also grown. All stacks are patterned into micromachined Hall bars with a channel width of 20 µm and length ranging from 50 to 100 µm. Figure 1(b) shows a device schematic with the definition of the coordinate system, while Figure 1(c) is an optical micrograph of a typical Hall bar. All patterned devices are vacuum annealed at 250°C for 1 h in 800 mT to set the exchange-bias direction. The top CoFe layer is pinned along the x-axis, with the magnetization parallel (anti-parallel) to the current when the annealing field is directed along x (−x). An exchange-bias field of $B_{EB} \sim 50$ mT on a blanket film with $t_{Ru} = 2$ nm is evidenced by magnetization curve in a field $B_x$, plotted in Figure 1(d). Figure 1(e) shows the anomalous Hall effect (AHE) voltage, $V_H$ as a function of out-of-plane field $B_z$ for a Hall bar with $t_{Ru} = 2$ nm. $V_H$ is measured with an applied current of 2 mA which corresponds to a current density of $j_{Pt} = 1.5 \times 10^{10}$ A m$^{-2}$ in the bottom Pt layer.

With the convention defined in Figure 1(b), the spin Hall effect (SHE) in Pt due to a charge current $j_{Pt}$ along x, generates a spin accumulation $\sigma$ polarised along −y at the top interface of the Pt layer. The pure spin current, $j_s$, relaxing within the adjacent CoFe free layer with moment $m$, exerts a Slonczewski-like SOT directed along $m \times (\sigma \times m)$ and a field-like SOT along $m \times \sigma$. The magnitudes of the two orthogonal SOT components are parametrised by the real and the imaginary parts of the complex spin-mixing conductance $G_{\uparrow\downarrow} = G' + iG''$ at the Pt/CoFe interface. Given the micrometric dimensions of our devices, a macrospin model is inapplicable and the switching should be described in terms of domain nucleation followed by thermally-assisted SOT-driven domain wall propagation. Efficient SOT-driven domain wall motion in a PMA material can be obtained when the wall assumes a Néel configuration (where the magnetization rotates in the xz plane) rather than a Bloch one (where the magnetization rotates in the yz plane). Bloch walls tend to be favoured in magnetic structures with PMA where the film thickness is negligible compared to other dimensions but an in-plane bias field along $x$ of order $B_x \approx 10$ mT is sufficient to transform a Bloch wall into a Néel wall. Since SOT-driven domain wall
motion is opposite for walls of opposite chirality (for instance $\uparrow \downarrow \rightarrow \downarrow \uparrow \rightarrow \uparrow \downarrow$), a reversed domain will either expand or collapse upon passing a current along the external field direction $[18–21]$. This leads to deterministic SOT switching where the preferred magnetization state depends on the sign of the injected current $j$. In our device, Néel domain walls with a particular sign of $m^\text{DW}$ are stabilised by IEC from top CoFe layer. Robust zero-field switching is achieved by pinning the magnetization of the top CoFe layer in the same direction as the applied current by exchange bias with antiferromagnetic IrMn.

We will focus on the switching properties of stacks with $t_{\text{Ru}} = 2$ nm and $t_{\text{Ru}} = 2.5$ nm for which the IEC via Ru is respectively antiferromagnetic (AFM) or ferromagnetic (FM). The pinned layers are exchange-biased along $+\hat{x}$. Figure 2(a-b) shows AHE loops with perpendicular applied field obtained at $I = \pm 30$ mA for the two stacks. While the loops taken at 2 mA did not show any noticeable asymmetry in the coercivity for positive and negative fields (Figure 2(c)), there is clearly a preferred switching direction in the high-current loops. This is in agreement with the presence of a torque that favours an orientation of $\mathbf{m}$ that depends on the sign of the injected current. In addition, upon changing the coupling from AFM to FM, the field shift of the AHE loops is reversed which indicates a sign change of $m^\text{DW}$. We further verified that the effect is absent in the control sample without the CoFe pinned layer.

Successive current pulses with a width of 10 ms are applied to the device and the Hall voltage is measured at a lower current of 2 mA after each one to probe the magnetization state of the free layer. Figure 2(c-d) shows the current-induced switching of the PMA layer of two devices measured at various external applied fields $B_x$. Both devices exhibit reversible SOT switching in the absence of an external field, but the $V_H - j_{\text{Pt}}$ loops of the two devices are opposite in sign due to opposite IEC for the two Ru thicknesses. We interpret this in terms of the presence of Néel domain walls in the free layer with a sign of $m^\text{DW}$, that is stabilised by the magnetic coupling from the pinned layer mediated via the Ru spacer. We also see that $V_H - j_{\text{Pt}}$ loops are reversed at $B_x \approx -40$ mT, which corresponds to the exchange bias field of the pinned CoFe. The switching of a device therefore depends on the sign of the coupling together with the value of $B_x$ relative to two characteristic fields of the system: the exchange bias field $B_{\text{EB}}$ and the IEC field $B_{\text{IEC}}$. The first is the effective field acting on the top CoFe layer coming from the direct exchange with the antiferromagnetic IrMn, while the second is the effective field acting on the bottom CoFe layer coming from the oscillatory interlayer coupling with the top CoFe via the Ru spacer. In the absence of external field ($B_x = 0$ mT), $m^\text{DW}$ is determined by the magnetization of the pinned layer and the sign of the IEC. When $B_x$ overcomes $B_{\text{EB}}$ ($-B_x > B_{\text{EB}}$), $\mathbf{m}$ of the pinned CoFe is reversed, which consequently changes the orientation of $m^\text{DW}$ and flips the $V_H - j_{\text{Pt}}$ loop. For both devices, the absence of a sign reversal for $-B_x$ ranging between zero and $B_{\text{EB}}$ indicates that $B_{\text{IEC}} > B_{\text{EB}} \approx 40$ mT. Furthermore, one expects to observe the breakdown of the AFM IEC at sufficiently high external bias fields $|B_x| > B_{\text{IEC}}$, which will again be indicated by the reversal of the $V_H - j_{\text{Pt}}$ loop. For $t_{\text{Ru}} = 2$ nm, the fact that no such reversal is seen for...
an applied field up to $|B_x| = 100\text{ mT}$ gives a lower limit to $B_{IEC}$. In order to test our model, we also annealed other devices with $t_{Ru} = 2\text{ nm}$ and $t_{Ru} = 2.5\text{ nm}$ in a magnetic field $B_x = -800\text{ mT}$ to set the exchange bias of the pinned CoFe layers in opposite directions compared to devices shown here, hence exerting opposite coupling to the domain walls within the thin CoFe. Those results confirm our explanation.

Finally, we used two independent methods to quantify the SOT in our heterostructures: spin Hall magnetoresistance (SMR)\cite{22, 26} and harmonic Hall measurements\cite{27, 28}. The measurements were performed on devices patterned from control stacks without the top pinning layers.

The SMR effect (Fig. 3) is caused by the simultaneous action of the spin Hall effect and the inverse spin Hall effect due to transmission and reflection of the spin current at the Pt/CoFe interface. The ratio between the reflected and the transmitted fractions of the spin accumulation depends on the relative orientation of the polarization of the electrons and the magnetic moment of the ferromagnet and on the spin-mixing conductance $G_{\uparrow\downarrow}$. If the imaginary part $G''_\sigma$ is negligible compared to the real part $G'_\sigma$, the SOT acting on the magnetization has the form $\mathbf{m} \times (\sigma \times \mathbf{m})$, with $\sigma \parallel y$. We confirm by harmonic Hall measurements that this is the case for Pt\cite{20, 28}. The torque is zero for $\mathbf{m} \parallel y$, when the absorption of spin current is at a minimum and the reflection at a maximum. Hence the longitudinal resistance $R_{xx}$ of the stack shows a $m_y^2$ dependence due to SMR of the Pt/CoFe bilayer.\cite{23, 27, 28,

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FIG. 2. (a-b) Anomalous Hall effect voltage as a function of the out-of-plane external field for different injected current values. While the low-current loop doesn’t show any asymmetry, the high-current loops show a preferred orientation of the magnetic moment. (c-d) Anomalous Hall effect voltage as a function of the injected current density in the Pt layer measured at different external fields $B_x$ along the current direction. (a-c) Sample with $t_{Ru} = 2\text{ nm}$, showing antiferromagnetic interlayer coupling. (b-d) Sample with $t_{Ru} = 2.5\text{ nm}$, showing ferromagnetic interlayer coupling. The top CoFe layer has been pinned in the $+x$ direction for both samples. The loops are shifted for clarity.
In addition, the effect of the SMR is seen in the transverse resistance \( R_{xy} \) as an additional contribution to the planar Hall effect with an \( m_x m_y \) dependency on the magnetization orientation. Angular scans of \( R_{xx} \) and \( R_{xy} \) in the \( zy \) plane are shown in Fig. 2(a). Assuming Pt is the unique source of SMR, it would be more appropriate to use the magnetoresistance due to SMR within the Pt layer \( \Delta R_{Pt}^{SMR} \) instead of the measured overall \( \Delta R_{xy} \) for rigorous SMR analysis \( \Delta R_{Pt}^{SMR} \) is related to \( \theta_{SH} \), the spin Hall angle of the Pt/CoFe system by the equation:

\[
\frac{\Delta R_{Pt}^{SMR}}{R_{Pt}^{0}} = \frac{2}{t_{Pt}} \frac{\lambda_{sf}^2 \rho_{Pt} G' \tanh^2 \frac{\mu_0 H}{2 \lambda_{sf}}}{1 + 2 \lambda_{sf} \rho_{Pt} G' \coth \frac{\mu_0 H}{2 \lambda_{sf}}} \tag{1}
\]

where \( R_{Pt}^{0} \) is the resistance of the Pt underlayer without SMR contributions, \( \rho_{Pt} \) is its resistivity and \( \lambda_{sf} \) is its spin diffusion length. The values of \( \Delta R_{Pt}^{SMR} \) have been determined by measuring the variation in the longitudinal resistance while rotating a 2T external magnetic field in the \( zy \) plane. The best fit of the Pt thickness \( t_{Pt} \) dependence of \( \Delta R_{Pt}^{SMR}/R_{Pt}^{0} \) with \( \theta_{SH} \), \( G' \) and \( \lambda_{sf} \) as parameters is shown in Figure 3(b).

We also measured the first and second harmonic Hall responses of the same device with \( t_{Pt} = 5 \) nm under a low frequency ac current excitation to quantify the effective spin-orbit fields. Considering the Hall voltage contribution from the anisotropic magnetoresistance and the SMR, we derive the longitudinal and transverse effective spin-orbit fields. As previously mentioned, the transverse field is negligible for Pt, confirming that the imaginary part of the spin-mixing conductance and the Rashba effect are very small. We found a spin Hall angle of \( \theta_{SH} = 11.2 \% \), in good agreement with our previous report on the YIG/Pt system. 24

In summary, we have demonstrated a novel approach to achieve zero-field SOT switching using the IEC via a nonmagnetic spacer. The preferred magnetization state of the free layer with PMA is reversed upon reversing the current polarity, the exchange-bias direction or the exchange coupling sign. The coupling cannot be explained by the stray field from a flat top CoFe layer, which is only antiferromagnetic and very small (~0.001 mT), nor by the stray field created by correlated surface roughness because the Néel orange peel mechanism is always ferromagnetic.

Our approach is scalable because the mechanism is independent of the area of the device as long as the dimensions are greater than the domain wall width, which is of the order of 25 nm. Furthermore, SOT switching has been demonstrated down to 30 nm dots with an applied field of 20 mT, which is well within the capability of our structure.

It should be possible to develop a new three-terminal device with magnetoresistive readout by using a SOT layer which is also the spacer for magnetic coupling. An iridium spacer which exhibits high spin-orbit coupling and relatively strong IEC might work. Our new switching concept, which is based on well-understood phenomena and materials, takes us a step closer to the practical realisation of spin-orbit torque applications involving manipulation of perpendicular nanomagnets, which include SOT-MRAM, SOT-based magnetic logic and an SOT-based magnetic racetrack.

**METHODS**

Sample and device fabrication

The stacks for demonstrating zero-field SOT switching are, from the substrate, Ta(1)/Pt(5)/CoFe(0.8)/Ru(3)/CoFe(1.5)/IrMn(10)/Pt(2) (thicknesses in nanometres) and those for SMR measurements and Pt resistivity fitting are Ta(1)/Pt(1)/CoFe(0.8)/Ru(3) with \( t_{Pt} \) ranging from 1 nm to 10 nm. The \( t_{Pt} = 5 \) nm sample from the latter series is also used for the harmonic Hall measurement and served as the reference for the switching experiment. All stacks are deposited on Si(001) substrates with 500 nm thermal oxide. Layers are grown by d.c. magnetron sputtering using an automated Shamrock sputtering tool with a chamber base pressure of 3 × 10^{-7} Torr and a growth pressure of ~2 mTorr. The growth rates of various metals are lower than 0.03 nm/s^{-1}, calibrated using X-ray reflectometry. The bottom Ta(1) layer serves as an adhesion layer for the Pt, improving the PMA of the CoFe. Eight-terminal Hall bar devices are fabricated using standard ultra-violet optical lithography and Ar ion milling. The Ti(5)/Cu(80)/Au(20) contacts are formed by electron-beam evaporation.

Characterisation

All sample characterisation is performed at room temperature. The saturation magnetization of the thin CoFe layer with PMA, obtained from the SQUID magnetometry, is \( \approx 1.2 \) MA m^{-1}, a value lower than the bulk. The angular dependence of the longitudinal and transverse magnetoresistance is measured at a d.c. current of 2 mA by fixing the device in a rotating 2.0 T magnetic field produced by a Multimag permanent magnet variable flux source. In harmonic Hall measurements, sinusoidal a.c. excitation is generated by a WF1946B waveform generator at a frequency of 1234.57 Hz and the current is measured on a 100 Ω series resistor using an EG&G 5210 lock-in amplifier. A small in-plane field is swept while the in-phase first harmonic and the out-of-phase second harmonic Hall signals are simultaneously detected using two SR830 lock-in amplifiers.
FIG. 3. Spin Hall magnetoresistance. (a) Longitudinal (upper panel) and transverse (lower panel) resistance for a sample of Ta(1)/Pt(2)/CoFe(0.8)/Ru(3) as a function of the magnetization direction in the zy plane. (b) Pt thickness dependence of the spin Hall magnetoresistance $\Delta R_{SMR}^{Pt}$. The solid line is the fit using eq. [1]. The error bars are given by the size of the dots.

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AUTHOR CONTRIBUTIONS STATEMENT

Y.C.L. and D.B. contributed equally to this work. Y.C.L. and D.B. designed the experiment and planned the study with the input from K.R. D.B. grew the samples and fabricated the devices. Y.C.L. and D.B. measured the devices. D.B. performed data analysis. Y.C.L. and D.B. wrote the manuscript with advice from J.M.D.C. and P.S.

ADDITIONAL INFORMATION

The authors declare no competing financial interests.