Supplementary material
Non-volatile electric control of spin-orbit torques in an oxide two-dimensional electron gas

Cécile Grezes¹, Aurélie Kandazoglou¹, Maxen Cosset-Cheneau¹†, Luis M. Vicente Arche², Paul Noël¹,³, Paulo Sgarro¹, Stephane Auffret¹, Kevin Garello¹, Manuel Bibes², Laurent Vila¹*, and Jean-Philippe Attané¹,⁴*

¹Université Grenoble Alpes / CEA / IRIG/ SPINTEC, Grenoble, France
²Unité Mixte de Physique, CNRS, Thales, Université Paris-Saclay, Palaiseau, France
³Department of Materials, ETH Zurich, 8093 Zurich, Switzerland
⁴Institut Universitaire de France
†Current address: Physics of Nanodevices, Zernike Institute for Advanced Materials, University of Groningen, 9747 AG Groningen, Netherlands
* e-mail: jean-philippe.attane@cea.fr, laurent.vila@cea.fr

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S1. Determination of the AHE and PHE contributions

The AHE and PHE contributions have to be measured to quantify the SOT effective fields using Eq. (2). This is achieved by measuring the first harmonic Hall resistance, as a function of the external magnetic field applied almost in-plane ($\theta_b = 85^\circ$) and at an angle $\phi_H \neq 0^\circ, 90^\circ$. Fig. S1 shows $R_{H,\text{ext}}$ as a function of $\mu_0H_{\text{ext}}$ for an angle $\phi_H = 45^\circ$ in the ungated state as an example. As AHE and PHE are respectively odd and even with respect to magnetization reversal, $R_{\text{AHE},\omega}$ and $R_{\text{PHE},\omega}$ can be separated by antisymmetrization and symmetrization of $R_{H,\text{ext}}$, respectively. Fig. S1b (Fig. S1c) shows the resulting $R_{\text{AHE},\omega}$ ($R_{\text{PHE},\omega}$) as a function of the external magnetic field ($\phi_H = 45^\circ$) for this example. The saturation value of the AHE resistance reads directly from the contrast of $R_{\text{AHE},\omega}$, yielding $R_{\text{AHE}} = 25.3 \, \Omega$. The PHE saturation resistance is deduced from the linear fit of $R_{\text{PHE},\omega}$ as a function of $\sin^2(\theta)$ (Fig. S1d), yielding $R_{\text{PHE}} = 1.7 \, \Omega$. The equilibrium angle of magnetization ($\theta_0$) as function of the applied external magnetic field is further determined from the first harmonic Hall measurement as \[ \theta_0 = \arccos \left[ \frac{R_{\text{AHE},\omega}(\mu_0H_{\text{ext}})}{R_{\text{AHE}}} \right]. \]

Figure S1 | Determination of the AHE and PHE contributions. a, First harmonic Hall resistance $R_{H,\text{ext}}$ as a function of the magnetic field applied almost in-plane ($\theta_b = 85^\circ$, $\phi_H = 0^\circ, 45^\circ, 90^\circ$). b, Antisymmetric AHE signal $R_{\text{AHE},\omega}$ of $R_{H,\text{ext}}(\phi_H=45^\circ)$ yielding $R_{\text{AHE}} = 25.3 \, \Omega$. c, Symmetric PHE signal $R_{\text{PHE},\omega}$ of $R_{H,\text{ext}}(\phi_H=45^\circ)$ d, $R_{\text{PHE},\omega}$ as a function of $\sin^2(\theta)$ showing the expected linear dependence, the slope yielding the PHE resistance $R_{\text{PHE}} = 1.7 \, \Omega$. The linear fit appears in red. All data have been measured in the ungated state at 10K with a 2D current density of $j = 4 \, \text{A.cm}^{-1}$.

S2. Electric-control of 2DEGs with anticlockwise hysteresis in SrTiO$_3$/Metal/CoFeB/MgO

The electric-control of the 2DEG has been investigated in several SrTiO$_3$/Metal/CoFeB/MgO samples with different metallic layers (Metal) in the scope of this study. Ta, Ru, Mg(0.9 nm)/CoFeB(0.9 nm)/MgO(1.8 nm)/Ta(1 nm) stacks were deposited onto 500 µm (001)-oriented SrTiO$_3$ substrates in order to create a 2DEG at the SrTiO$_3$/Metal interface, following an identical sample preparation (cf. § Methods). The stacks were patterned into 1 µm wide and 10 µm wide Hall bar devices by electron-beam lithography, and sample-wide back-gates of Ti(10 nm)/Au(100 nm) were deposited by evaporation. Fig. S2 shows the sheet resistance $R_s$ as a function of the applied gate electric-field for SrTiO$_3$/Mg/CoFeB/MgO and SrTiO$_3$/Ru/CoFeB/MgO samples, at the temperature of 10 K and after initializing the ferromagnet in the up magnetization state. Similar anticlockwise hysteresis to
those seen in SrTiO₃ \(\text{Ta} / \text{CoFeB/MgO} \) samples are observed, with two switchable and remanent high and low resistance states. This confirms the appearance of charge trapping effect at different SrTiO₃/Metal interface. The resistance difference inside the hysteresis, as magnetization follows a different path, which explains the curve opening for the positive \( M \). Fig. S3a (Fig. S3c) shows \( R_{SOT} \) as a function of \( \mu \times H_{ext} \) applied at \( \theta = 85^\circ \) and \( \phi = 0^\circ \) \( (90^\circ) \) for negative and positive gate electric-fields of \( \pm 3.2 \text{kV} \text{cm}^{-1} \). The ANE contribution \( R_{ANE} \) is observed as the difference of \( R_{SOT} \) measured at zero field for positive and negative sweeps of \( \mu \times H_{ext} \), together with a constant offset \( R_{Offset} \) for \( E_g = \pm 3.2 \text{kV} \text{cm}^{-1} \) respectively. Both \( R_{Offset} \) and \( R_{ANE} \) can be subtracted from the raw data using [1]:

\[
R_{SOT,2\omega} = R_{H,2\omega} - R_{ANE} - \frac{R_{H,2\omega}}{2R_{ANE}} - R_{Offset}
\]  

S3. Separating SOT effective fields from thermal contributions

To determine the SOT effective fields, the second harmonic Hall resistance \( R_{H,2\omega} \) must be decorrelated from other contributions, corresponding to the magneto thermal contributions and to the effect of voltage probes misalignment [1][2]. The ac current flowing into the Hall bar generates a modulated temperature gradient, which induces a second harmonic component to the Hall voltage via two types of theromelectric voltages: the Seebeck effect and the Anomalous Nernst-Ettingshausen effect (ANE). The Seebeck effect, as well as the asymmetry of the voltage probes, induces an offset \( R_{Offset} \) in \( R_{H,2\omega} \). The ANE, on the other hand, is perpendicular to the temperature gradient and to the magnetization easy axis, and induces a second harmonic contribution proportional to the ANE in \( R_{H,2\omega} \). Fig. S3a (Fig. S3c) shows \( R_{H,2\omega} \) as a function of \( \mu \times H_{ext} \) applied at \( \theta = 85^\circ \) and \( \phi = 0^\circ \) \( (90^\circ) \) for negative and positive gate electric-fields of \( \pm 3.2 \text{kV} \text{cm}^{-1} \). The ANE contribution \( R_{ANE} \) is observed as the difference of \( R_{H,2\omega} \) measured at zero field for positive and negative sweeps of \( \mu \times H_{ext} \), together with a constant offset \( R_{Offset} \) for \( E_g = \pm 3.2 \text{kV} \text{cm}^{-1} \) respectively. Both \( R_{Offset} \) and \( R_{ANE} \) can be subtracted from the raw data using [1]:

\[
R_{SOT,2\omega} = R_{H,2\omega} - R_{ANE} - \frac{R_{H,2\omega}}{2R_{ANE}} - R_{Offset}
\]  

Fig. S3b (Fig. S3d) shows the resulting SOT anti-damping like signal (field-like signal) after subtraction of the thermal effects contributions \( R_{Offset} \) and \( R_{ANE} \). The data shown are taken inside the hysteresis. The arrows indicate the sweeping field direction, emphasizing the inversion of the anti-damping-like torque direction under the two different gates. Inside the hysteresis, the magnetization direction (theta angle path) is different for the positive \( M_+ \) and negative \( M_- \) sweeps of magnetic field. Consequently, its susceptibility to the field-like term is different inside the hysteresis, as magnetization follows a different path, which explains the curve opening for the field-like signal. Outside the hysteresis, the curves are well closing-up, as shown in Fig. S3c. Thermal signals arising from Nernst effect are well corrected, as evidenced by the crossing close to 0 at zero-field (for in-plane thermal gradient along current direction).
**S4. SiO$_2$/Ta/CoFeB/MgO reference sample characterization**

A SiO$_2$/Ta/CoFeB/MgO reference sample has been prepared for comparison, with identical deposits to those made for the SrTiO$_3$/Ta/CoFeB/MgO samples. The stack was patterned into 1 µm wide and 10 µm long Hall cross-bars for electrical measurements. An input current of magnitude 400 A was injected along the x direction, and the longitudinal $R_L$, and transverse Hall resistances $R_H$ were measured as a function of the external magnetic field $\mu_0H_{ext}$. As shown in Fig. S4a, the temperature dependence of the sheet resistance of the device is characteristic of a metallic behavior, as expected from the metallic CoFeB/Ta bilayer, with a sheet resistance reaching 0.69 kΩ.sq$^{-1}$ at 10K. This sheet resistance is significantly lower than that of the CoFeB/Ta bilayer in SrTiO$_3$/Ta/CoFeB/MgO sample, confirming that the CoFeB/Ta bilayer is partially oxidized via oxygen reduction in contact of SrTiO$_3$.

Fig. S4b shows the anomalous Hall resistance as a function of the applied out-of-plane magnetic field. A square-shaped magnetic hysteresis loop is observed, indicating that the CoFeB has a perpendicular magnetization. To quantify the spin-orbit torques, harmonic Hall voltage measurements are performed with the magnetic field $\mu_0H_{ext}$ applied almost in-plane ($\theta_H = 85^\circ$, $\phi_H = 0, 90^\circ$). Fig. S4c and d shows the first and second harmonic Hall resistances $R_{H,1,2\omega}$, respectively. Following the procedure described in the main text, the anti-damping like torques and field like-torques are determined after subtracting the thermal effects contribution to $R_{H,2\omega}$, yielding $\mu_0H_{ext}j = -0.15$ mT/(A.cm$^{-1}$) and $\mu_0H_{ext}/j = -0.43$ mT/(A.cm$^{-1}$). Notably, the SOT-AD effective field of the SiO$_2$/Ta/CoFeB/MgO reference sample is negative, of opposite sign compared to that of the SrTiO$_3$/Ta/CoFeB/MgO system in the low 2DEG resistivity state. This confirms that the SOT arises from the 2DEG via the Edelstein effect for SrTiO$_3$/Ta/CoFeB/MgO in low 2DEG resistivity state, rather than from a residual Spin Hall effect in the Tantalum layer. Note that the AD-SOT in the SiO$_2$/Ta/CoFeB/MgO reference
sample is slightly higher than that of the SrTiO₃/Ta/CoFeB/MgO samples in high resistivity state, in agreement with the partial oxidation of the CoFeB/Ta bilayer of the latter.

Figure S4 | SiO₂/Ta/CoFeB/MgO reference sample. a, Temperature dependence of the stack sheet resistance Rₛ. b, Out-of-plane (θₓ = 90°) magnetic field dependence of the Hall resistance at 10 K, showing well-defined up and down perpendicularly magnetized states. c, First RH₁(θₓ) and d, second RH₂(θₓ) harmonic Hall resistances as a function of the magnetic field applied almost in-plane (θᵧ = 85°, φᵧ = 0°, 90°) at 10K. All data have been measured with a 2D current density of j = 4 A.cm⁻².

S5. SOT contributions from the 2DEG and the Tantalum layer

The 2DEG and the Ta layer constitute two parallel channels of conduction, with two corresponding SOT contributions to the total SOT. In the following, we refer to HAD,2DEG(HAD,Ta) the intrinsic SOT contribution from the 2DEG (Ta layer) alone. In a simple model, one can assume that the total SOT is the sum of the contributions (in mT), weighted by the fraction of current injected in the corresponding conduction channels:

\[ H_{AD,signal} = pH_{AD,2DEG} + (1-p)H_{AD,Ta} \]

where \( p \) is the fraction of current injected in the 2DEG, displayed in Fig. 4b, and \( pH_{AD,2DEG} \) and \( (1-p)H_{AD,Ta} \) the 2DEG-induced and Ta-induced anti-damping like SOT, respectively. The ratio of 2DEG-induced SOT to Ta-induced SOT is:

\[ r_{AD} = \frac{pH_{AD,2DEG}}{(1-p)H_{AD,Ta}} = \frac{H_{AD,signal} - (1-p)H_{AD,Ta}}{(1-p)H_{AD,Ta}} \]

As a bulk metal, the intrinsic Ta-induced SOT \( H_{AD,Ta} \) does not depend on the gate electric-field, and is revealed directly in the high resistivity state \( H_{AD,Ta} = H_{AD,signal}(Eg,max) \) when there is no current in the 2DEG (i.e \( p = 0 \)) and where the SOT is constant. The left panel of the Figure R3 below shows the requested ratio \( r_{AD} \) of 2DEG-induced SOT to Ta-induced SOT at 10K, as a function of the gate electric-field. At large positive gates, the SOT is mostly due to the 2DEG, whose contribution is up to 82 times larger than that of the Ta layer. The variations of the overall SOT with the electric-field are due both to the current redistribution in the stack when varying the 2DEG resistivity, and to the variations of the conversion with the 2DEG Fermi level position. The temperature dependence of \( r_{AD} \) in the low resistivity state can be read directly from Fig. 5b with \( H_{AD,Ta}(T) = H_{AD,signal}(Eg,max, T) \), and is displayed on the right panel (for \( j = 2 \text{ A. cm}^{-1} \)).
Figure S5 | 2DEG-induced SOT to Ta-induced SOT contributions. a, Ratio of 2DEG-induced SOT to Ta-induced SOT as a function of gate electric-field at the temperature of 10K and for $j= 4\,\text{A}\cdot\text{cm}^{-1}$. b, Temperature dependence of the ratio of 2DEG-induced SOT to Ta-induced SOT in the low resistivity state ($E_g = +2.6\,\text{kV}\cdot\text{cm}^{-1}$) for $j=2\,\text{A}\cdot\text{cm}^{-1}$.

REFERENCES

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