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Ultralow-power field-free magnetization switching via oxide interfacial Quasi-two-dimensional electron gas

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The practical implementation of spin-orbit torque (SOT) technologies requires efficient spin source that enables field-free switching of perpendicular magnetization with minimal power consumption. Here, we demonstrate that a symmetry-breaking oxide interface Quasi-two-dimensional electron gas (Q-

2DEG), created by argon ion bombardment of miscut SrTiO₃ (001), can serve as such a high-performance spin source. The surface Q-2DEG exhibit good ohmic contact with the ferromagnetic metal, thereby allowing the miscut Q-2DEG spin source to fully realize its advantages of high charge-spin conversion efficiency and intrinsic symmetry breaking. Along the low-symmetry direction of the miscut oxide surface, the Q-2DEG exhibits both large anomalous spin polarization and conventional spin polarization, with an anomalous spin polarization angle as high as 14.57°. In miscut Q-2DEG/CoGd heterostructures, we achieve deterministic field-free switching with an ultralow critical current density of $8.1 \times 10^4 \text{ A}\cdot\text{cm}^{-2}$ and the power dissipation density of $7 \times 10^{12} \text{ W}\cdot\text{m}^{-3}$. This miscut surface oxide Q-2DEG capitalizes on strong Rashba spin-orbit coupling and symmetry engineering, establishing a foundation for integrable, low-power spin logic and memory technologies.

As semiconductor scaling approaches physical limits in the post-Moore era, integrated circuits face fundamental bottlenecks in power dissipation and memory bandwidth^{1,2}. Spintronic devices, which leverage the electron spin for data storage and processing, offer a compelling path forward through their non-volatility, high speed, and ultralow standby power³. However, their practical implementation requires the efficient electrical manipulation of magnetic order for seamless CMOS integration⁴. Current-induced spin-orbit torque (SOT) enables this control via spin current-induced angular momentum transfer, providing the fundamental writing mechanism for next-generation nonvolatile memories and spin logic architectures^{5,6}.

Despite its promise, SOT technology faces a fundamental materials dichotomy. Conventional heavy metals achieve metallic conductivity but generate spin polarization predominantly in the film plane⁷, necessitating external magnetic fields for deterministic perpendicular switching⁸, which inevitably impedes high-density integration. While structural engineering or low-symmetry crystals^{9–12} can enable field-free operation, heavy metals inherently suffer from limited spin Hall efficiency, requiring prohibitive critical current densities ($>10^6 \text{ A}\cdot\text{cm}^{-2}$). Conversely, topological insulators (TIs) offer high conversion efficiency^{13–15} through spin-momentum locking, yet their high resistivity and rigid crystal symmetries, incompatible with perpendicular magnetization, cause substantial resistive power losses. These trade-offs define the criteria for an ideal spin source as highlighted in recent technology roadmaps¹⁶, which must simultaneously deliver: (i) high intrinsic conversion efficiency to minimize current density, (ii) tailorable symmetry to enable field-free perpendicular switching and (iii) high electrical conductivity to suppress power consumption.

Oxide two-dimensional electron gases (2DEGs) emerging at perovskite interfaces uniquely satisfy all these criteria. They exhibit high carrier mobility accompanied by strong Rashba spin-orbit coupling^{17,18}. Importantly, their entangled charge-spin-lattice-orbital degrees of freedom offer a versatile platform for materials design: the tunable metallic conductivity can be exploited to minimize power loss, while the spin polarization sensitive to crystal symmetry allows for the potential activation of anomalous spin components. These properties have enabled efficient charge-spin interconversion^{18–22}, long-range spin transport^{23–25}. However, achieving highly efficient

deterministic field-free magnetization switching in these systems remains elusive. This bottleneck stems primarily from the “buried” nature of the 2DEG conducting layer, where the inevitable Schottky barriers^{26–28} severely block spin injection into ferromagnets (Upper panel of Fig. 1a). Simultaneously, the potential for anomalous spin generation remains prohibited in 2DEGs, where high crystallographic symmetry (Upper panel of Fig. 1b) imposes selection rules that forbid the out-of-plane spin polarization essential for field-free switching.

Here, we surmount these critical bottlenecks by engineering a symmetry-broken surface quasi-two-dimensional electron gas (Q-2DEG) on a miscut SrTiO₃ (001) substrate. By utilizing argon-ion bombardment²⁹, we effectively transform the otherwise prohibitive Schottky barrier into a highly transparent ohmic contact (Lower panel of Fig. 1a). Concurrently, vicinal miscut breaks the in-plane rotation and mirror symmetries (Lower panel of Fig. 1b), activating the otherwise forbidden out-of-plane spin polarization (σ_z) essential for deterministic switching. This synergistic strategy fully exploits of the giant intrinsic charge-spin conversion efficiency at the oxide interface. We thereby demonstrate robust field-free perpendicular magnetization switching in Q-2DEG(m)/CoGd heterostructures with an ultralow critical current density $8.1 \times 10^4 \text{ A} \cdot \text{cm}^{-2}$ and power dissipation density $7 \times 10^{12} \text{ W} \cdot \text{m}^{-3}$ (Fig. 1c), values that are orders of magnitude lower than those of state-of-the-art heavy metals and topological insulators. These findings bridge the long-standing gap between high-mobility oxide electronics and practical spintronics, establishing a platform for ultralow-power spin logic and memory technologies.

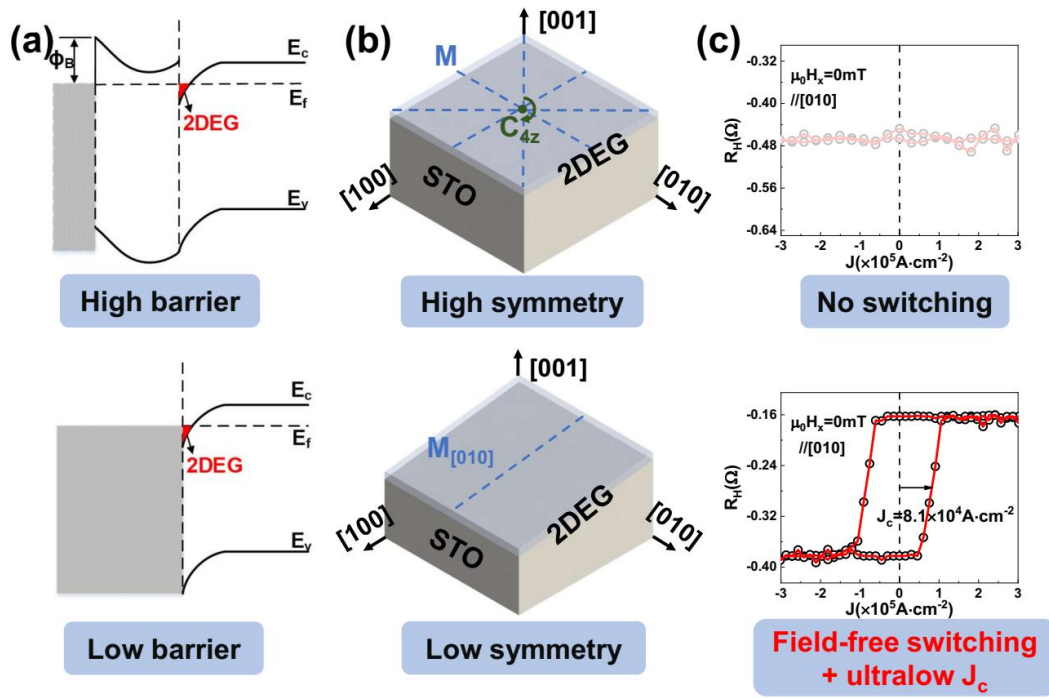


Fig. 1 | Ohmic contact formation and symmetry breaking enable field-free switching in oxide Q-2DEG heterostructures. (a) Energy-band schematics comparing spin injection at conventional “buried” 2DEG interface (upper), where a Schottky barrier blocks spin transport, with the engineered surface Q-2DEG (lower), where argon-ion bombardment creates a transparent ohmic contact. (b) Symmetry breaking at the Q-2DEG surface induced by 0.3° miscut. Loss of in-plane mirror and rotation symmetries activates the out-of-plane spin polarization. (c) Field-free perpendicular magnetization switching in Q-2DEG(m)/CoGd heterostructures, achieved at critical current density $J_c \approx 8.1 \times 10^4 \text{ A}\cdot\text{cm}^{-2}$, orders of magnitude lower than heavy metal and topological insulator-based devices.

Formation of oxide Q-2DEG

We fabricated the surface Q-2DEG via optimized argon-ion bombardment (300 eV) of 0.3° miscut SrTiO_3 (001) substrates (miscut direction along $[100]$), creating an

oxygen-vacancy-induced conducting layer²⁹ (Methods and Supplementary Note 1). High-resolution transmission electron microscopy (HR-TEM) resolves the Q-2DEG thickness at approximately 2.07 nm, with distinct interfaces visible between the crystalline SrTiO₃ substrate, irradiated SrTiO₃ layer and surface carbon contamination (Fig 2a, inset). The measured thicknesses at different positions are consistent with the empirical formula (Supplementary Note 1).

Energy-dispersive X-ray spectroscopy (EDX) elemental chemical mapping (right panel of Fig. 2a) reveals an irregular ~2 nm Sr-rich surface layer atop the crystal lattice, in agreement with the TEM measurements. Transport characterization confirms the metallic behavior: temperature-dependent resistivity yields a residual resistance ratio (RRR) of 558.5 and room-temperature resistivity of 1057.79 $\mu\Omega$ cm, which is 5–6 orders of magnitude lower than that of pristine SrTiO₃ (001) substrates (Fig. 2b). The carrier concentration $n(\sim 3 \times 10^{21} \text{ cm}^{-3}$ at 300 K, Fig. 2c) exhibits weak temperature dependence above 50 K, with an upturn at lower temperatures attributed to activation of multiple conductive channels³⁰. Shubnikov-de Haas (SdH) oscillations in magnetoresistance confirm the 2D nature of the electron gas, persisting up to 3.4 K (Fig 2d)³¹. Notably, the bombardment power provides tunable control over both transport properties and thickness (Supplementary Note 2), as established in prior work²⁹. Critical to spintronic functionality, the Q-2DEG surface exhibits ohmic contact behavior (linear I-V, Fig. 2e), in stark contrast to the insulating nature of untreated SrTiO₃ and the Schottky barrier characteristics of buried 2DEG in SrTiO₃/LaAlO₃ heterostructures (Supplementary Note 3). This ohmic character eliminates interfacial

power dissipation and enables efficient spin current injection into adjacent ferromagnetic layers.

The structural symmetry of this surface Q-2DEG enables the essential spin physics. Bulk SrTiO₃ adopts centrosymmetric cubic perovskite structure (space group $Pm\bar{3}m$, point group O_h). At the ideal (001) interface, the structural confinement reduces this to the tetragonal C_{4v} , preserving four-fold rotational axis (C_{4z}) and four mirror planes ($M_{[100]}$, $M_{[010]}$, $M_{[110]}$, $M_{[1\bar{1}0]}$), symmetries that forbid out-of-plane spin polarization in linear response (upper panel of Fig. 1b). However, the [100] miscut introduces a stepped surface that breaks the C_{4z} rotation axis and the $M_{[100]}$, $M_{[110]}$ and $M_{[1\bar{1}0]}$ mirror planes. The system descends to monoclinic $C_s(m)$, retaining only the $M_{[010]}$ mirror perpendicular to the step edges (lower panel of Fig. 1b). This specific symmetry reduction lifts the selection rule, permitting an out-of-plane spin component (σ_z) via the spin-momentum locking, consistent with the Neumann principle. Such a symmetry-allowed out-of-plane spin polarization is further corroborated by our effective Hamiltonian model calculations (Supplementary Note 16).

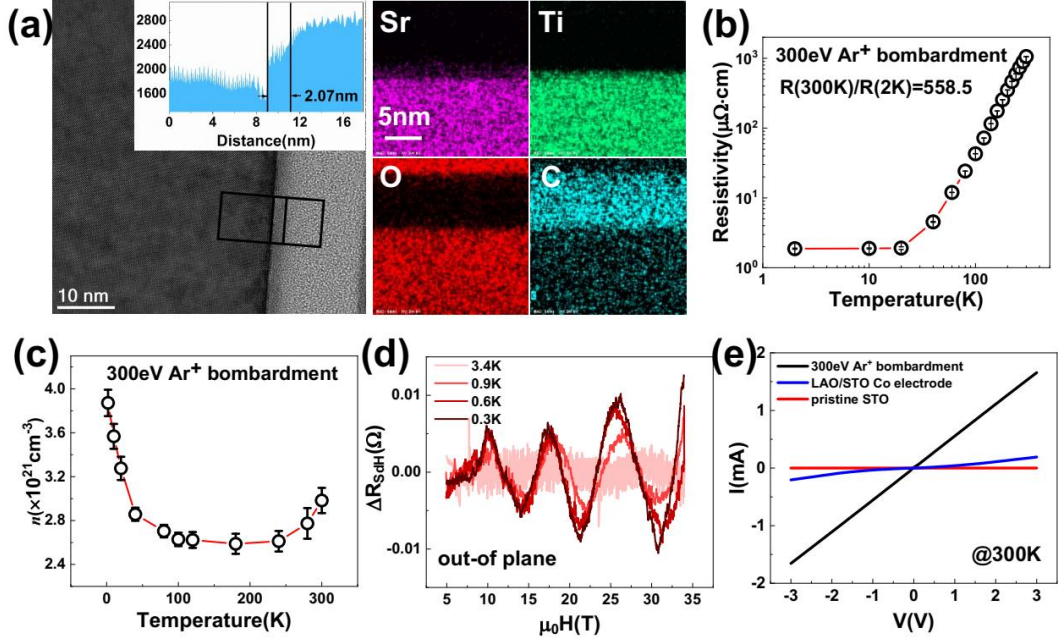


Fig. 2 | Structural and transport characterization of the engineered Q-2DEG. (a) Cross-section HR-TEM image (left) and EDX elemental mapping of Sr, Ti, O, and C distributions (right). Inset: Line profile across the blue-boxed region. (b) Temperature-dependent resistivity of the 300-eV-irradiated Q-2DEG. (c) Temperature-dependent carrier concentration n of the sample irradiated with 300 eV (d) Shubnikov-de Haas oscillations confirming 2D metallicity up to 3.4 K. (e) I-V characteristics comparing the ohmic contact of the 300-eV-irradiated Q-2DEG (black) against the Schottky behavior of LAO/STO/Co (blue) and insulating pristine STO (blue).

Field-free perpendicular magnetization switching

We demonstrate deterministic field-free perpendicular magnetization switching in miscut Q-2DEG/CoGd heterostructures (miscut Q-2DEG is abbreviated as Q-2DEG(m)) at room temperature, achieved through engineered symmetry breaking. The Hall bar devices with the stack structure Q-2DEG(m) (2.1 nm)/Ti (2 nm)/CoGd (4 nm)/

Cu (4 nm) were fabricated along miscut SrTiO₃ [010] and [100] directions (Figs. 3a and 3b). The CoGd layer exhibits temperature-compensated ferrimagnetism, with Co-dominated moments at room temperature (Supplementary Note 4).

Deterministic field-free magnetization switching occurred exclusively along the low-symmetry [010] direction (Fig. 3c and Supplementary Note 6), consistent with the anisotropic out-of-plane spin polarization (σ_z) calculated using our effective Hamiltonian model (Supplementary Note 16). No field-free switching was observed along the high-symmetry [100] direction or in non-miscut Q-2DEG/CoGd samples (Fig. 3d and Supplementary Note 7), confirming that miscut-induced symmetry breaking is essential. The critical switching current density for the low-symmetry [010] direction in miscut Q-2DEG(m)/CoGd is as low as $8.1 \times 10^4 \text{ A}\cdot\text{cm}^{-2}$, which is far below the theoretical limit of $10^7 \text{ A}\cdot\text{cm}^{-2}$ for Ta/CoFeB systems³².

Control experiments rule out alternative mechanisms. Neither the pristine STO/CoGd (no spin source) nor the STO/LAO/CoGd sample (Schottky barrier) exhibited current-induced magnetization switching (Supplementary Note 8). The STO/CoGd/Pt sample showed field-assisted switching, excluding the CoGd inhomogeneity effects.

The critical current density depends on both charge-spin conversion efficiency (spin Hall angle) and magnetic layer parameters, described by $J_c = \frac{2e}{\hbar} \frac{M_S t_F}{\theta_{SH}} \left(\frac{H_k}{2} - \frac{H_x}{\sqrt{2}} \right)$ ³³, where e denotes the elementary charge, $\hbar$ is the reduced Planck constant, M_S is the saturation magnetization, t_F represents the ferromagnetic layer thickness, θ_{SH} is the spin Hall angle, H_k is the effective magnetic anisotropy field, and H_x refers to the external

in-plane magnetic field. To exclude the magnetic layer effects on the critical current density, we selected a reference perpendicular magnetic multilayer with a composition of Cu (2 nm)/[Co (0.25 nm)/Ni (0.6 nm)]₅/Cu (4 nm) ([Co/Ni]₅) with thickness close to that of CoGd. But the M_S and H_k of [Co/Ni]₅ are 2–3 times larger than those of CoGd. Field-free switching was achieved along the [010] direction of miscut Q-2DEG(m)/[Co/Ni]₅ samples (Supplementary Note 9), with a critical current density of $1.32 \times 10^5 \text{ A} \cdot \text{cm}^{-2}$, which is slightly larger than that of Q-2DEG(m)/CoGd, but much lower than that of Pt/[Co/Ni]_n³⁴. This confirms that the low critical current density originates from the Q-2DEG's intrinsic high charge-spin conversion efficiency.

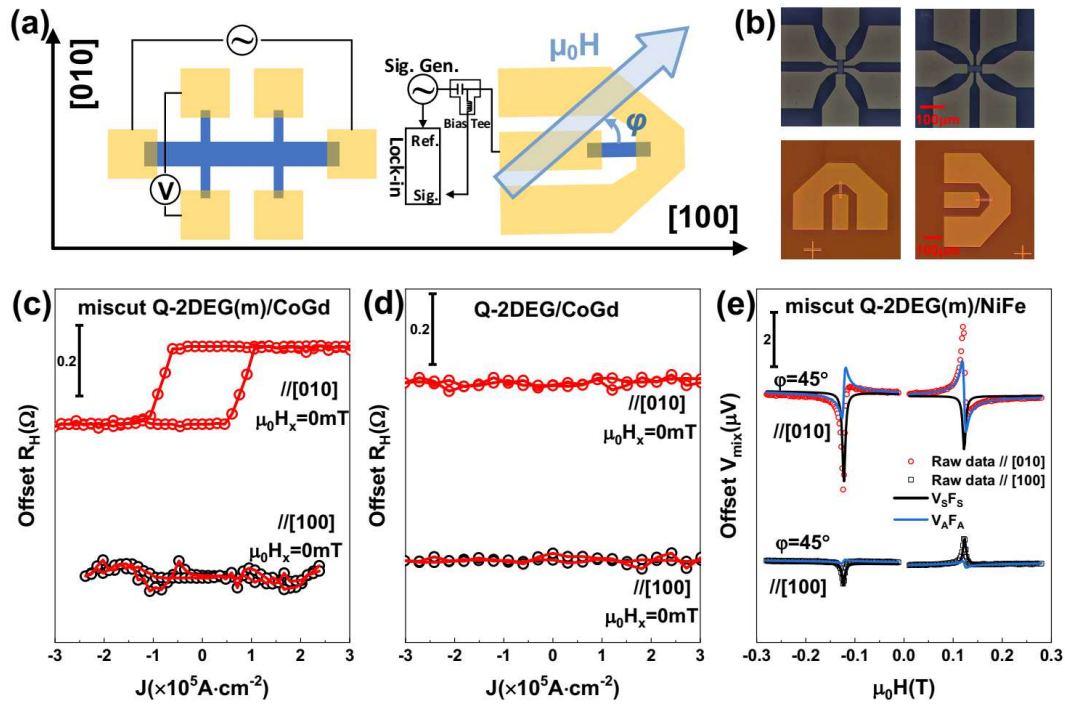


Fig. 3 | Field-free perpendicular magnetization switching and spin-orbit torque characterization. (a) Schematic of Hall bar device for current-induced magnetization switching (left) and ST-FMR measurements (right). (b) Optical micrographs of Hall bar devices (top) and ST-FMR coplanar waveguides (bottom) fabricated along [010] and

[100] directions. (c) Field-free switching in miscut Q-2DEG(m)/CoGd samples along [010] and [100] directions, showing exclusive switching along the low-symmetry direction at $J_c = 8.1 \times 10^4 \text{ A} \cdot \text{cm}^{-2}$. (d) Absence of field-free switching in non-miscut Q-2DEG/CoGd devices along both directions. (e) ST-FMR spectra of Q-2DEG(m)/NiFe along [010] and [100].

Characterization of charge-spin conversion efficiency

We quantified the anisotropic charge-spin conversion efficiency of Q-2DEG using spin-torque ferromagnetic resonance (ST-FMR)³⁵ at room temperature (Fig. 3a, right) with the sample consisting of Q-2DEG(m) (2.1 nm)/NiFe (8 nm)/MgO (1.5 nm)/Ta (2 nm) (Q-2DEG(m)/NiFe). Detailed measurement and calculation procedures are provided in Supplementary S10. ST-FMR spectra at 10 GHz (Fig. 3e) reveal sizeable antisymmetric lineshapes (blue line) for [010] devices, indicating out-of-plane spin-orbit torque components absent in [100] devices. We extract the conventional and anomalous spin-torque efficiencies: for [010], $\xi_{DL}^y = -0.33$ and $\xi_{DL}^z = -0.09$; for [100], $\xi_{DL}^y = -0.22$ and $\xi_{DL}^z = 0.01$ (Supplementary Note 10). The anomalous spin polarization angle $\theta = \arcsin(\xi_{DL}^z / \sqrt{(\xi_{DL}^z)^2 + (\xi_{DL}^y)^2})$ quantifies deviation from in-plane spin polarization. Devices along the miscut [010] direction exhibit an out-of-plane spin polarization angle of 14.57° , nearly seven times larger than along [100] (2.1°), and also much larger than non-miscut control samples (3.87° for [010] and 1.65° for [100]), confirming that miscut activates the anomalous spin component essential for field-free switching (Supplementary Table S2).

Harmonic Hall voltage measurements on the Q-2DEG/CoGd independently

confirm high spin-orbit efficiency, yielding $\xi_{DL} = 0.56 \pm 0.02$ (Supplementary Note 11), comparable to literature values 0.45–5.4 for oxide interfaces³⁶ and consistent with the anisotropic ST-FMR results. The slight discrepancy between techniques likely reflects the interface state differences and the directional versus total efficiency measurement geometries. Micromagnetic simulations using experimentally extracted spin-torque efficiencies confirm that field-free switching occurs exclusively for [010]-oriented miscut Q-2DEG(m), validating the anomalous spin polarization angle as the sole determinant of zero-field switching capability (Supplementary Note 12).

Optimization of power dissipation density

We optimized the Q-2DEG(m) spin source to minimize the power dissipation density $P = J_c^2 \cdot \rho$, achieving $P = 7 \times 10^{12} \text{ W} \cdot \text{m}^{-3}$ and $J_c = 8.1 \times 10^4 \text{ A} \cdot \text{cm}^{-2}$ through systematical tuning of argon-ion bombardment energy and substrate miscut angle (Supplementary Note 13). The power dissipation density exhibits a nonmonotonic dependence on bombardment energy, reaching a minimum at 300 eV (Fig. 4a). This trend tracks resistivity modulation, indicating that bombardment tunes the conductive properties of the Q-2DEG while maintaining constant spin-orbit efficiency and thus unchanged J_c . The miscut angle dependence reveals that switching amplitude ΔR_H rises rapidly from 0° to 0.3° then saturates (Fig. 4b). While our model predicts that the out-of-plane spin accumulation s_z scales linearly with the miscut angle in the perturbative regime, the observed saturation at larger angles likely originates from complex surface reconstructions or enhanced scattering at the step edges, which may deviate from the

idealized perturbative picture and degrade the spin generation efficiency (Supplementary Note 16).

Figure 4c maps materials in the efficiency space of the anomalous versus conventional spin polarization (ξ_{DL}^z versus ξ_{DL}^y). Symmetry-broken materials (TaIrTe₄ and WTe₂)^{37–44} typically exhibit trade-offs: moderate ξ_{DL}^y with small ξ_{DL}^z , or vice versa (Supplementary Note 14). The oxide Q-2DEG with miscut along [010] uniquely combines strong conventional polarization with substantial anomalous polarization. The [100] direction, lacking miscut-induced symmetry breaking, shows only conventional response.

Figure 4d benchmarks power dissipation against critical current density for field-free SOT systems, including HMs, antiferromagnets, semimetals, oxide and TIs^{10,11,39,45–64}. Conventional HMs cluster at high J_c (10^6 – 10^7 A·cm⁻²) and high P (10^{14} – 10^{17} W·m⁻³). TIs reduce J_c but suffer from high resistivity, leaving power dissipation unchanged. Semimetals and oxides partially improve but remain above 10^{14} W·m⁻³ (Supplementary Note 15). The Q-2DEG breaks this barrier by two orders of magnitude achieving $P = 7 \times 10^{12}$ W·m⁻³ and $J_c = 8.1 \times 10^4$ A·cm⁻² through its unique combination of metallic conductivity and giant spin-orbit efficiency.

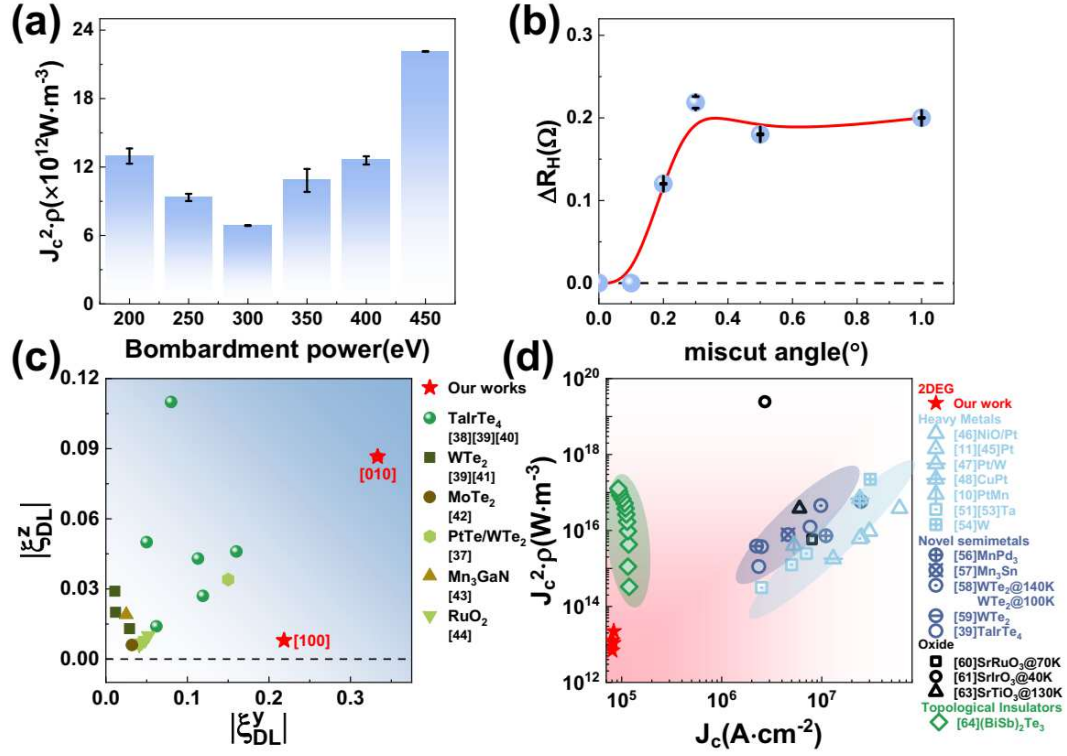


Fig. 4 | Optimization and benchmarking of spin-orbit torque efficiency. (a) Power dissipation density versus argon-ion bombardment energy, showing minimum $P = 7 \times 10^{12} \text{ W} \cdot \text{m}^{-3}$ at 300 eV for 0.3° miscut samples. (b) Field-free switching amplitude ΔR_H versus miscut angle. (c) Anomalous versus conventional spin-torque efficiency (ξ_{DL}^z vs. ξ_{DL}^y) for symmetry-broken materials. (d) Benchmarking power dissipation versus critical current density for field-free SOT systems. Data points for heavy metals (blue), semimetals (purple), topological insulators (green), and this work (red star).

Discussion and outlook

We establish symmetry-engineered oxide Q-2DEGs as a distinct materials class for spin-orbit torque applications, overcoming the fundamental efficiency-conductivity trade-off that has constrained heavy metals and topological insulators. The Q-2DEG(m) combines three essential attributes unattainable in conventional systems: metallic

conductivity for impedance matching, giant Rashba spin-orbit coupling for efficient charge-spin conversion, and tunable crystallographic symmetry for field-free operation. Surface engineering transforms the “buried” 2DEG interface—previously inaccessible due to Schottky barriers—into a transparent ohmic contact, fully exploiting these intrinsic advantages.

Beyond memory, the Q-2DEG platform enables multifunctional spintronic architectures. The high carrier mobility supports long-range spin transport as both source and channel, while gate-tunable carrier density, absent in metallic heavy metals, allows electric field control of spin-orbit torque strength. Integration with ferroelectric oxides further permits non-volatile voltage gating of spin polarization, opening paths to reconfigurable spin logic with ultralow standby power. Moreover, the entangled charge-spin-lattice-orbital degrees of freedom in perovskite oxides provide a rich parameter space for quantum spin phenomena. Strain, electrostatic gating, and optical excitation can modulate spin-orbit coupling and symmetry, enabling dynamically tunable spin textures for topological spintronics and quantum information applications.

By bridging high-mobility oxide electronics with practical spintronics, this work establishes a materials platform where symmetry is a design parameter rather than a fixed constraint. The Q-2DEG paradigm points toward CMOS-compatible, ultralow-power spin logic and reconfigurable architectures that transcend the limitations of current charge-based and spin-based technologies.

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Methods

Sample preparation and thin film characterization

The quasi-two-dimensional electron gas (Q-2DEG) is obtained by Argon ion (Ar^+) bombardment of SrTiO_3 (001) substrates with a series of miscut angles. The miscut direction is along the [100] crystallographic direction, with miscut angles of 0.1° , 0.2° , 0.3° , 0.5° , and 1° , denoted as Q-2DEG (m). In contrast, the non-miscut samples have a miscut angle less than 0.02° , denoted as Q-2DEG. Our work focuses primarily on samples with a miscut angle of 0.3° . First, miscut SrTiO_3 (001) substrates are pre-cleaned in a buffered oxide etch (BOE) etching solution, then annealed in an O_2 gas flow at 1000°C for 3 hours to form a step terrace structure. Subsequently, a Kaufman-type ion etcher is used to bombard the substrate surface, thereby preparing the Q-2DEG. The $\text{SrTiO}_3/\text{LaAlO}_3$ samples are epitaxially grown on (001)-oriented SrTiO_3 substrate by pulsed laser deposition (PLD, KrF , $\lambda = 248\text{ nm}$). The substrate is TiO_2 terminated by reacting in deionized water for 30 min and etching in BOE, then the SrTiO_3 substrate is annealed at 950°C for 90 min to achieve an atomically smooth surface. The LaAlO_3 thin film is subsequently deposited on the top of TiO_2 -terminated SrTiO_3 (001) substrate by PLD at a temperature of 700°C with the laser energy density of 1 to 1.25 J/cm^2 , and 2×10^{-5} to 1×10^{-4} mbar oxygen pressure, and is then gradually cooled down to room temperature.

The magnetic multilayers include out-of-plane magnetized Q-2DEG(m)/Ti (2 nm)/CoGd (4 nm)/Cu (4 nm) [denoted as Q-2DEG(m)/CoGd], Q-2DEG/Ti (2 nm)/CoGd (4 nm)/Cu (4 nm) [denoted as Q-2DEG/CoGd], as well as in-plane

magnetized Q-2DEG(m)/NiFe (8 nm)/MgO (1.5 nm)/Ta (2 nm) [Q-2DEG(m)/NiFe] and Q-2DEG/NiFe (8 nm)/MgO (1.5 nm)/Ta (2 nm) [Q-2DEG/NiFe]. The out-of-plane magnetized samples were employed for magnetization switching measurements, while the in-plane magnetized sample was utilized for ST-FMR measurements. A series of control samples were designed and grown, including miscut SrTiO₃ (001)/Ti (t_{Ti} = 1, 2 nm)/CoGd (4 nm)/Cu (4 nm) [STO/CoGd], miscut SrTiO₃ (001)/ Ti (t_{Ti} = 1, 2 nm)/CoGd (4 nm)/Pt (4 nm) [STO/CoGd/Pt], SiO₂/ Ti (t_{Ti} = 1, 2 nm)/CoGd (4 nm)/Cu (4 nm) [CoGd], SrTiO₃(100)/LaAlO₃/Ti (2 nm)/CoGd (4 nm)/Cu (4 nm) (5 uc)/ [STO/LAO/CoGd] and SiO₂/Pt (2 nm)/NiFe (8 nm)/MgO (1.5 nm)/Ta (2 nm) [Pt/NiFe]. Table S1 summarizes all the sample and device information.

All samples were grown at room temperature via magnetron sputtering. CoGd films were prepared by co-sputtering of elemental Co and Gd targets with deposition powers of 11 W and 30 W, respectively, yielding an approximate atomic ratio of Co:Gd = 0.81:0.19. MgO films were deposited by RF sputtering at a working pressure of 2 mTorr. NiFe films were grown using an alloy target, while all other unspecified metallic layers were deposited from their corresponding elemental targets via direct current (DC) sputtering at a pressure of 0.8 mTorr.

The structural analysis was carried out via X-ray diffraction $2\theta/\omega$ scan and rocking curve using a monochromated Cu K α radiation (λ = 1.54056 Å). The high resolution transmission electron microscopy (HR-TEM) measurements were performed using a Cs-corrected FEI Themis at 200 keV. The high-angle annular dark field STEM (HAADF-STEM) images were acquired using a convergence semiangle of 20 mrad and

collecting scattering from >65 mrad. The energy-dispersive X-ray spectroscopy (EDX) was performed for elemental mapping using a Bruker EDX system consisting of four silicon drift detectors in the Themis microscope. The STEM specimens were prepared by the focused ion beam lift-out technique using an FEI DualBeam Helios G5 HX at 30 kV. The final polish is 1 kV, and the TEM camera is ceta $4k \times 4k$.

Device fabrication

To investigate the current-induced magnetization switching and anisotropic charge-spin conversion of Q-2DEG, out-of-plane magnetized Q-2DEG(m)/CoGd, Q-2DEG/[Co/Ni], STO/CoGd, SiO₂/CoGd, STO/CoGd/Pt and in-plane magnetized Q-2DEG/NiFe, STO/NiFe were patterned into Hall bars ($20 \mu\text{m} \times 100 \mu\text{m}$, Figs. 2A and S4) and microstrip-type coplanar waveguide (CPW) devices ($20 \mu\text{m} \times 100 \mu\text{m}$, Fig. 3D), respectively, using a combination of photolithography and reactive ion etching. Then, a top electrode of Cr (5 nm)/ Au (100 nm) was deposited by DC magnetron sputtering. Other samples were also fabricated into devices using the same microfabrication process.

Magnetotransport measurements

The transport properties of the sample were investigated using the cryogen free measurement system (CFMS, Cryogenic Limited). A Keithley 6221 was employed as the current source during the measurements, while the Hall voltage and magnetoresistance were synchronously collected by a lock-in amplifier SR830. High-field magnetotransport measurements were performed at the HM magnet of Steady

High Magnetic Field Facility (High Magnetic Field Laboratory, Chinese Academy of Sciences, Hefei).

Current-induced switching measurements

A DC pulsed current with pulse width of 1ms was applied by a Keithley 6221 current source. Then, the Hall resistance was recorded by a Keithley 2182 Nanovoltmeter using a current of 100 μA .

ST-FMR measurements

During the ST-FMR measurements, I_{RF} with a power of 19 dBm was applied along the microstrip by Rohde & Schwarz SMA-100B RF and microwave signal generator, while the ST-FMR signals (V_{mix}) were measured by a Stanford Research SR865 lock-in amplifier.

Harmonic hall measurements

During the harmonic measurements, a low-frequency alternation current with frequency of 1327 Hz was generated by Stanford Research SR830. The first- and second-harmonic voltages (V_{ω} and $V_{2\omega}$) were measured using SR830 Lock-in amplifiers.

Supplementary Files

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