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Electric field control of spin-orbit torque switching in a spin-orbit ferromagnet single layer

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To achieve a desirable magnitude of spin-orbit torque (SOT) switching and realise multifunctional spin logic and memory devices utilising SOT, controlling the SOT manipulation is vitally important. In conventional SOT bilayer systems, researchers have tried to control the switching behaviour via interfacial oxidisation; however, the switching efficiency is limited by the interface quality. A current-induced effective magnetic field in a single layer of a ferromagnet with strong spin-orbit interactions, the so-called spin-orbit ferromagnet, can be utilised to induce SOT. In spin-orbit ferromagnet systems, electric field application has potential for manipulating the spin-orbit interactions via carrier concentration modulation. In this work, we demonstrate that SOT switching can be successfully controlled via an external electric field using a (Ga,Mn)As single layer. By applying a gate voltage, the switching current density can be solidly and reversibly manipulated with a large ratio of 14.5%, which is ascribed to the successful modulation of the interfacial electric field. Our findings help further the understanding of the magnetisation switching mechanism and advance the development of gate-controlled SOT devices.

Spin-orbit torque (SOT) has been proposed as a promising candidate to control the magnetisation of ferromagnetic materials, showing great potential for realisation of spintronic memory devices with better stability, higher scalability, faster information processing speed and lower energy consumption. To further enhance the SOT magnetisation switching efficiency, researchers have explored various effective methods. First, the most generally used approach is to find materials with a large spin Hall angle θ_{SH} that can generate a large spin current, which can be utilised to effectively decrease the critical switching current density J_c ^{1,2}. Those materials with large θ_{SH} are utilised in bilayer systems, where the spin current generated in a nonmagnetic layer is injected into the adjacent ferromagnetic layer and exerts a torque to switch the magnetisation. In bilayer systems, the SOT switching can be manipulated by controlling the interfacial oxidation³⁻⁶. However, the spin injection is limited by the interface quality, which hinders further decreases in J_c . To overcome this limitation, a new class of materials called spin-orbit ferromagnets, including ferromagnetic topological insulators and the ferromagnetic semiconductor Mn-doped GaAs ((Ga,Mn)As), have recently been found to be very promising for highly efficient magnetisation switching due to the strong spin-orbit-induced effective magnetic field and the large spin polarisation⁷⁻¹⁰. Especially in (Ga,Mn)As, an extremely low J_c (4.6×10^4 A cm⁻²) has been demonstrated by suppressing the contribution of the field-like term with a current-induced magnetic field¹¹. In ferromagnetic topological insulators, electric field application has been demonstrated to control J_c via modulation of the density and type of surface carriers^{10, 12-13}. However, the switching process is still improvable in terms of the switching hysteresis and its completeness¹⁰. To achieve a desirable magnitude and realise multifunctional SOT spin logic and memory devices with a simple structure and high efficiency, manipulating the SOT in an appropriate spin-orbit ferromagnet single layer is strongly required. The single-

crystalline ferromagnetic semiconductor (Ga,Mn)As is one of the best material systems for this purpose, where the Dresselhaus and Rashba effective fields (H_D and H_R) induced by the spin-orbit interactions contribute to an in-plane spin component that can exert a strong torque on the magnetisation⁸. Because both H_D and H_R are strongly influenced by the internal electric field^{14,15}, external electric field application is expected to achieve effective manipulation of the SOT in (Ga,Mn)As.

In this Article, we demonstrate that the SOT switching behaviour in a ferromagnetic (Ga,Mn)As single layer can be manipulated by applying an electric field using a solid gate electrode, as shown in Fig. 1a. By changing the sign and magnitude of the gate voltage V_g , the interfacial electric field and hole concentration of (Ga,Mn)As are manipulated, enhancing or suppressing the spin-orbit interactions. Because the spin-orbit interactions couple the spin of a hole with its momentum and generate H_D and H_R (Fig. 1b)¹⁶⁻¹⁹, H_D and H_R are very sensitive to the applied electric field. By applying a positive V_g , we show that the enhancement of H_D and H_R contributes to an increase in the SOT switching efficiency, decreasing J_c . Our findings provide a promising method for efficient modulation of SOT switching by applying an electric field to a single spin-orbit ferromagnetic layer.

Magnetisation reversal in the Au/Cr/AlO_x/(Ga,Mn)As system

The sample structure examined in this study is (Ga_{0.94}Mn_{0.06})As (7 nm)/In_{0.3}Ga_{0.7}As (500 nm)/GaAs (50 nm) grown on a GaAs (001) substrate by molecular beam epitaxy (MBE). Due to the 500-nm-thick lattice-relaxed insulating In_{0.3}Ga_{0.7}As layer, a tensile strain is applied to the (Ga_{0.94}Mn_{0.06})As thin film, inducing perpendicular magnetic anisotropy (PMA). As shown in Fig. 1a, the film was patterned into a crossbar (red parts in Fig. 1a) with a size of 0.5 μm (width) $\times$ 2

1 μm (length) by electron beam lithography for transport measurements. The Au (100 nm)/Cr (5
 2 nm) electrodes (yellow parts in Fig. 1a), which also work as heat sinks, were deposited with
 3 electron beam evaporation. For the solid gate electrode, 40-nm-thick AlO_x was deposited by
 4 atomic layer deposition at 150 °C as a dielectric layer. (See Supplementary Note 1 in the
 5 Supplementary Information for the detailed device fabrication process.) Through characterisation
 6 of the anomalous Hall effect (AHE), the PMA is confirmed by measuring the Hall resistance R_H
 7 with sweeping of a magnetic field H_z applied perpendicular to the film plane. In Fig. 2a, the $R_H -$
 8 H_z curve (see the black curve) shows an obvious square-like character, where R_H varies between
 9 approximately $\pm 0.6 \text{ k}\Omega$. The coercivity H_c is 300 Oe, as shown in the square-like $R_H - H_z$ curve,
 10 and we see an obvious anisotropic magnetoresistance (AMR) effect (see the red curve in Fig. 2a),
 11 where R reaches the maximum value when the magnetisation starts to be reversed by H_z .

12 In addition to a magnetic field, a current J can also be utilised to switch the magnetisation.
 13 As shown in Fig. 2b, with the help of a small external magnetic field $H_{\text{ext}} = 300 \text{ Oe}$ for
 14 deterministic magnetisation reversal, R_H can be changed between $\pm 0.6 \text{ k}\Omega$ by sweeping J along
 15 the in-plane direction, which is consistent with the AHE result in Fig. 2a; this result indicates that
 16 the magnetisation can be fully reversed between the $+z$ and $-z$ directions with a rotation angle of
 17 180 deg by J . For $J // [\bar{1}10]$ (see the black curve in Fig. 2b and the illustration of torques in Fig.
 18 2c), the spin component $\hat{\mathbf{G}}_x$ induced by the effective field is along the $[\bar{1}\bar{1}0]$ direction, as shown
 19 in Fig. 1b, which exerts an anti-damping torque $\hat{\mathbf{\tau}}_{\text{ST}}$ on the magnetic moment. $\hat{\mathbf{\tau}}_{\text{ST}}$ is proportional
 20 to $\hat{\mathbf{m}} \times \hat{\mathbf{G}}_x \times \hat{\mathbf{m}}$, and the direction of $\hat{\mathbf{\tau}}_{\text{ST}}$ is the same as that of $\hat{\mathbf{G}}_x$. Here, $\hat{\mathbf{m}}$ represents the unit
 21 magnetisation vector. With the assistance of the torque $\hat{\mathbf{\tau}}_{\text{ext}}$ induced by H_{ext} , *i.e.*, $\hat{\mathbf{\tau}}_{\text{ext}} = -\hat{\mathbf{m}} \times \hat{\mathbf{H}}_{\text{ext}}$
 22 (here, $\hat{\mathbf{H}}_{\text{ext}}$ represents the vector of H_{ext}), $\hat{\mathbf{\tau}}_{\text{ST}}$ overcomes the torque $\hat{\mathbf{\tau}}_{\text{an}}$ induced by the
 23 perpendicular anisotropy field H_{an} , *i.e.*, $\hat{\mathbf{\tau}}_{\text{an}} = -\hat{\mathbf{m}} \times \hat{\mathbf{H}}_{\text{an}}$ (here, $\hat{\mathbf{H}}_{\text{an}}$ represents the vector of H_{an}),

and reverses the magnetic moment when J increases. In the case of $J // [110]$ (see the orange curve in Fig. 2b and the illustration of torques in Fig. 2d), the induced spin component $\hat{\sigma}_y$ points in the $[1\bar{1}0]$ direction, which is parallel to $\hat{\tau}_{\text{ext}}$ and opposite to $\hat{\tau}_{\text{an}}$. Therefore, with increasing J , $\hat{\tau}_{\text{ST}}$ is enhanced, and magnetisation reversal occurs. Here, we note that a small hysteresis window appears when J is between $12 \times 10^5 \text{ A cm}^{-2}$ and $17 \times 10^5 \text{ A cm}^{-2}$ along the $[1\bar{1}0]$ direction (see the black curve in Fig. 2b), which might result from slight phase separation of the $(\text{Ga}_{0.94}\text{Mn}_{0.06})\text{As}$ layer.

In the magnetisation switching behaviour shown in Fig. 2b, J_c is $8.2 \times 10^5 \text{ A cm}^{-2}$ at 40 K for $J // [\bar{1}10]$. By changing J towards the $[110]$ direction, J_c is found to be increased to $10.5 \times 10^5 \text{ A cm}^{-2}$. This occurs because H_R is induced in the $\text{Au/Cr/AlO}_x/(\text{Ga,Mn})\text{As}$ system by the breaking of the structure inversion symmetry with the 40-nm-thick AlO_x layer and the Au/Cr electrode. As shown in Fig. 1b, under $J // [\bar{1}10]$, H_R is parallel to H_D , which enhances the total effective field H_{eff} along the in-plane direction, where $H_{\text{eff}} = H_D + H_R$, and makes the spin component exert a strong SOT on the magnetisation. In contrast, under $J // [110]$, the direction of H_R is opposite to that of H_D , which suppresses H_{eff} ($H_{\text{eff}} = H_D - H_R$) and weakens the SOT. Therefore, the switching process is hindered by H_R when J flows along the $[110]$ direction, resulting in an increase in J_c . The aforementioned results indicate that the direction of the induced spin component is always along H_D (see Fig. 1b). Hence, we can conclude that H_D is dominant during the SOT switching in the $\text{Au/Cr/AlO}_x/(\text{Ga,Mn})\text{As}$ system and that H_R can assist the switching process for $J // [\bar{1}10]$ but hinders it for $J // [110]$.

Manipulation of SOT switching via a gate electric field

To achieve manipulation of the SOT switching with an electric field, we applied a gate voltage V_g to the gate electrode shown in Fig. 1a. First, we measured the electrical characteristics of the crossbar device, where the source-drain current I_{SD} was measured as a function of the source-drain voltage V_{SD} at 40 K by applying various V_g of 0 V, ± 1 V, ± 5 V, ± 10 V, ± 15 V and ± 20 V, as shown in Fig. 3a. Here, V_{SD} ranging from +0.1 V to -0.1 V was applied with a step of 0.001 V. The $I_{SD} - V_{SD}$ curves in Fig. 3a show an obvious ohmic character, meaning that ohmic contacts are formed in the crossbars. The contacts remained in good condition and were not destroyed during the measurements. By applying V_g , we found that I_{SD} was varied, indicating that I_{SD} can be manipulated by V_g . To more clearly understand the change in I_{SD} when applying different V_g , I_{SD} modulation ratios at various V_g are plotted in Fig. 3b based on the results shown in Fig. 3a. Here, the modulation ratio is defined by $\Delta I_{SD} / I_{SD} (V_g = 0) \times 100\%$, where ΔI_{SD} is the I_{SD} modulation defined by $\Delta I_{SD} = I_{SD} (V_g) - I_{SD} (V_g = 0)$. In Fig. 3b, an obvious I_{SD} change occurs that is modulated by V_g . For $V_g < 0$, the I_{SD} modulation ratio is positive, indicating that the negative V_g increases the hole concentration in the (Ga_{0.94}Mn_{0.06})As layer. In contrast, for $V_g > 0$, the I_{SD} modulation ratio is negative, resulting from the decrease in the hole concentration in the (Ga_{0.94}Mn_{0.06})As thin film.

Next, SOT switching was induced by sweeping J along the $[\bar{1}10]$ direction with application of a V_g of ± 10 V, as shown in Fig. 3c. From the results, the application of the positive $V_g = +10$ V decreases J_c from 8.2×10^5 to 7.6×10^5 A cm⁻², which means that the SOT switching efficiency is enhanced for $V_g > 0$. Meanwhile, for $V_g = -10$ V, J_c increases to 8.7×10^5 A cm⁻², indicating that the negative V_g hinders the switching process to some extent. Hence, by applying the electric field ($V_g = \pm 10$ V), J_c can be efficiently modulated by $\sim 14.5\%$ [$= (8.7 - 7.6) / 7.6 \times 100\%$]. Figure 3d shows the manipulation of the SOT switching ($J // [\bar{1}10]$) at different V_g of ± 5 V, ± 10 V, ± 15

V and ± 20 V at 40 K (see Supplementary Note 3 in the Supplementary Information for details), from which we can conclude that a positive V_g decreases J_c and that a negative V_g increases J_c . These results indicate that the switching behaviour is solidly reversibly modulated via the electric field.

Mechanism of the electric field control of the SOT switching

The physical mechanism of the electric field modulation of the SOT switching in the (Ga,Mn)As layer can be attributed to the successful modulation of the interfacial electric field E . As shown in Fig. 4a, when V_g is 0, an internal electric field E_0 is generated because of the existence of a thin depletion layer in the (Ga_{0.94}Mn_{0.06})As layer in the vicinity of the AlO_x layer, as shown in Fig. 4d. By applying a positive V_g , the depletion is enhanced, as shown in Fig. 4e, which generates an additional interfacial electric field E_1 that points in the same direction as E_0 , as shown in Fig. 4b. Therefore, the total E becomes larger and contributes to a strong spin-orbit interaction, which enhances H_R and H_D . Then, H_R and H_D induce a large spin component along the in-plane direction, which exerts a strong SOT on the magnetisation and enables a highly efficient switching process with a small J_c . When V_g is negative, holes accumulate near the interface between the AlO_x and (Ga,Mn)As layers based on a capacitor model, which increases the hole concentration near the AlO_x layer, as shown in Fig. 4f. Then, the direction of E_1 is reversed, as shown in Fig. 4c, and the total E is suppressed. The suppressed E weakens H_R and H_D , resulting in a decrease in the strength of the SOT. Therefore, the magnetisation switching process is suppressed, and J_c increases.

By changing the direction of J from $[\bar{1}10]$ to $[110]$, the J_c modulation ratio obtained by applying V_g decreases from 14.5% to 4.9% $[= (10.8 - 10.3)/10.3 \times 100\%]$, as shown in Fig. 5a,

where J_c is estimated to be $10.3 \times 10^5 \text{ A cm}^{-2}$ at $V_g = +10 \text{ V}$ and $10.8 \times 10^5 \text{ A cm}^{-2}$ at $V_g = -10 \text{ V}$. The decrease in the J_c modulation ratio indicates that both H_D and H_R are influenced by V_g and that the total manipulation effect is much stronger for $J // [\bar{1}10]$. This is reasonable because H_D and H_R point in the same direction for $J // [\bar{1}10]$, and the modulation effects are superimposed. In contrast, when applying J along the $[110]$ axis, the directions of H_D and H_R are opposite, which reduces the modulation effect obtained by applying the gate electric field because the total enhancement or suppression effects of H_D and H_R cancel out. Hence, a small modulation ratio of J_c is realized.

To check the influence of the modulation of H_c by the gate bias voltage, R_H is measured by sweeping H_z along the $[001]$ direction at $V_g = 0$ and $\pm 10 \text{ V}$. As shown in Fig. 5b, with changing V_g , H_c is nearly constant at approximately 300 Oe, indicating that H_c is not a determining factor in the electric field control of the SOT switching. In addition, Fig. 5b shows that R_H varies between $\pm 0.587 \text{ k}\Omega$ when sweeping H_z at $V_g = +10 \text{ V}$. At $V_g = -10 \text{ V}$, R_H varies between $\pm 0.571 \text{ k}\Omega$. Therefore, R_H can be slightly modulated by V_g with a modulation ratio of only 2.8% [= $(0.587 - 0.571) / 0.571 \times 100\%$]. Additionally, from the results shown in Fig. 3a, R is estimated to be $193 \text{ k}\Omega$ at $V_g = +10 \text{ V}$ and $186 \text{ k}\Omega$ at $V_g = -10 \text{ V}$. In ferromagnets, $R_H = R_s M + R_0 B$, where R_s is the anomalous Hall coefficient and is proportional to either R or R^2 , depending on the AHE mechanism (skew or side-jump scattering)²⁰. M is the magnetisation, R_0 is the ordinary Hall coefficient, and B is the magnetic field. If R_s is proportional to R , then the saturation magnetisation can be considered to be slightly modulated by V_g with a modulation ratio of only -0.9% [= $(0.587/193 - 0.571/186) / (0.571/186) \times 100\%$]. If R_s is proportional to R^2 , then the modulation ratio of the saturation magnetisation is -4.5% [= $(0.587/193^2 - 0.571/186^2) / (0.571/186^2) \times 100\%$]. However, both values are much smaller than the modulation of J_c ($\sim 14.5\%$).

for $J // [\bar{1}10]$). Therefore, the saturation magnetisation also does not have a significant influence on the electric field control of the SOT switching process. To check the effect of the gate modulation of H_{an} , we changed the direction of the external magnetic field from $[001]$ to $[\bar{1}10]$ (along the y axis), where H_y represents the magnetic field intensity (Fig. 5c). From the comparison of H_c in Fig. 5b ($H_c = 300$ Oe) and Fig. 5c (coercivity $H_c' = 7580$ Oe), a 2.3° [$= \arcsin(300/7580)$] misalignment of the magnetic field occurs due to the misalignment of the magnet and/or the sample, resulting in an additional AHE signal. Therefore, an out-of-plane component of the external magnetic field with a value of 12 Oe ($= 300 \times \sin(2.3^\circ)$) exists during the current-induced SOT switching, but it is negligibly small. Here, the three curves shown in Fig. 5c can be found to overlap with each other, which means that H_{an} is constant when changing V_g and that the influence of the modulation of H_{an} can also be excluded as a determining factor in the successful manipulation of the SOT switching via the electric field.

Conclusions

In this work, the manipulation of SOT switching via a gate electric field is achieved, which can be ascribed to the successful modulation of the interfacial electric field. By applying a positive V_g , the strength of the electric field is enhanced, which strengthens the total effective field in (Ga,Mn)As and assists the magnetisation switching. In contrast, a negative V_g results in a smaller effective field, which decreases the switching efficiency and increases J_c . This finding provides an approach towards reversible modulation of the SOT switching in a single layer of a spin-orbit ferromagnet via electric fields, which will advance the development of energy-efficient gate-controlled spin-torque devices and help further the understanding of the switching mechanism.

Methods

Sample preparation. A 7-nm-thick (Ga_{0.94}Mn_{0.06})As thin film was grown on a semi-insulating GaAs (001) substrate in an ultrahigh-vacuum MBE system. After removal of the surface oxide layer of the GaAs substrate at 580 °C, a 50-nm-thick GaAs buffer layer was grown to obtain an atomically smooth surface. After that, the substrate was cooled to 450 °C, and a 500-nm-thick In_{0.3}Ga_{0.7}As layer was grown to induce a tensile strain in the (Ga_{0.94}Mn_{0.06})As layer, giving rise to PMA. Then, the sample was cooled to approximately 290 °C for growth of the 7-nm-thick (Ga_{0.94}Mn_{0.06})As layer. The growth process was monitored *in situ* by means of reflection high-energy electron diffraction. The Curie temperature T_C of the (Ga_{0.94}Mn_{0.06})As thin film was estimated to be 75 K. After the device fabrication process, the T_C increased to 112 K, which might be caused by the annealing process resulting from the increase in the sample temperature during the device fabrication process (see Supplementary Note 2 in the Supplementary Information for details).

Transport measurements. For the SOT measurements, a Keithley 2636A was used as the current source for applying a direct current, and a Keithley 2400 was used for applying a gate voltage. The Hall voltage was measured with another Keithley 2400. The measurements were carried out at 40 K.

Data availability

Acknowledgements

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Author Contributions

Sample preparation: M. J. and H. A.; measurements: M. J.; data analysis: M. J., S. O. and M. T.; writing and project planning: M. J., S. O. and M. T.

Additional information

The authors declare no competing financial interests. Reprints and permission information is available online at <http://npg.nature.com/reprintsandpermissions/>. Correspondence and requests for materials should be addressed to M. T.

Supplementary information is available for this paper at URL.

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Figure 1 | Schematic illustrations of the device structure and the effective magnetic field. a, Schematic of the SOT device structure. The channel width of the crossbar is $0.5 \mu\text{m}$, and the channel length is $2 \mu\text{m}$. The yellow parts are the capping layers on the electrodes consisting of Au (100 nm)/Cr (5 nm), which also work as heat sinks. The current J flows in the $(\text{Ga}_{0.94}\text{Mn}_{0.06})\text{As}$ layer with perpendicular magnetisation from the source electrode (S) to the drain electrode (D), and the Hall resistance R_H is obtained by measuring the Hall voltage V_H along the $[110]$ direction orthogonal to the S-D direction. An electric field is applied by the gate voltage V_g . **b,** Dresselhaus-like (red) and Rashba-like (light blue) effective magnetic fields (H_D and H_R , respectively) for hole momenta along different crystallographic directions in the tensile-strained $(\text{Ga}_{0.94}\text{Mn}_{0.06})\text{As}$ thin film. (k_x, k_y, k_z) is the wave vector of holes.

Figure 2 | Characterisation of the AHE and AMR effect, and SOT switching. **a**, Perpendicular magnetic field H_z dependence of the Hall resistance R_H and resistance R of (Ga_{0.94}Mn_{0.06})As at 40 K. **b**, Field-assisted SOT switching with $J \parallel [\bar{1}10]$ and $[110]$ in a 7-nm-thick (Ga_{0.94}Mn_{0.06})As thin film at 40 K, where the magnitude of H_{ext} is 300 Oe. **c**, **d**, Illustrations of the torques exerted by the spin component ($\hat{\tau}_{\text{ST}}$), the external field ($\hat{\tau}_{\text{ext}}$) and the anisotropy field ($\hat{\tau}_{\text{an}}$) with $J > 0$ for $J \parallel [\bar{1}10]$, $H_{\text{ext}} \parallel [\bar{1}10]$ (**c**) and $J \parallel [110]$, $H_{\text{ext}} \parallel [\bar{1}\bar{1}0]$ (**d**). $\hat{m}$ is in the y - z plane (**c**) and x - z plane (**d**). (Source data are provided as a Source Data file.)

Figure 3 | V_g dependence of the I_{SD} modulation and SOT switching with $J // [\bar{1}10]$. **a**, I_{SD} - V_{SD} characteristics and **b**, I_{SD} modulation ratio with the application of various gate voltages V_g of 0 V, ± 1 V, ± 5 V, ± 10 V, ± 15 V and ± 20 V at 40 K. V_{SD} ranging from +0.1 V to -0.1 V was applied with a step of 0.001 V. **c**, Field-assisted SOT switching by applying V_g of 0 and ± 10 V. **d**, Plot of J_c obtained with various V_g in a 7-nm-thick (Ga $_{0.94}$ Mn $_{0.06}$)As thin film at 40 K. Here, $J // [\bar{1}10]$ and $H_{ext} = 300$ Oe. In this measurement, we changed V_g in the order of 0 V $\rightarrow$ +5 V $\rightarrow$ -5 V $\rightarrow$ +10 V $\rightarrow$ -10 V $\rightarrow$ +15 V $\rightarrow$ -15 V $\rightarrow$ +20 V $\rightarrow$ -20 V. (Source data are provided as a Source Data file.)

Figure 4 | Schematic illustrations of the interfacial electric field and the band structure.

Schematic illustration of the gate voltage modulation of the interfacial electric field under **a**, $V_g = 0$ V, **b**, $V_g > 0$ V, and **c**, $V_g < 0$ V. Schematic illustration of the band structure of Au/Cr/AlO_x/(Ga,Mn)As under **d**, $V_g = 0$ V, **e**, $V_g > 0$ V, and **f**, $V_g < 0$ V.

Figure 5 | V_g dependence of SOT switching with $J \parallel [110]$, H_c , and H_{an} . **a**, Field-assisted SOT switching with V_g of 0 and ± 10 V in a 7-nm-thick (Ga_{0.94}Mn_{0.06})As thin film at 40 K. Here, $J \parallel [110]$ and $H_{\text{ext}} = -300$ Oe. **b**, Out-of-plane magnetic field H_z dependence and **c**, in-plane magnetic field H_y dependence of the Hall resistance R_H of (Ga_{0.94}Mn_{0.06})As with V_g of 0 and ± 10 V at 40 K. The inset of (a) shows the coordinate relationship. (Source data are provided as a Source Data file.)

Figures

Figure 1

Schematic illustrations of the device structure and the effective magnetic field. a, Schematic of the SOT device structure. The channel width of the crossbar is $0.5 \mu\text{m}$, and the channel length is $2 \mu\text{m}$. The yellow parts are the capping layers on the electrodes consisting of Au (100 nm)/Cr (5 nm), which also work as heat sinks. The current J flows in the $(\text{Ga}_{0.94}\text{Mn}_{0.06})\text{As}$ layer with perpendicular magnetisation from the source electrode (S) to the drain electrode (D), and the Hall resistance R_H is obtained by measuring the Hall voltage V_H along the $[110]$ direction orthogonal to the S-D direction. An electric field is applied by the gate voltage V_g . b, Dresselhaus-like (red) and Rashba-like (light blue) effective magnetic fields (H_D and H_R , respectively) for hole momenta along different crystallographic directions in the tensile-strained $(\text{Ga}_{0.94}\text{Mn}_{0.06})\text{As}$ thin film. (k_x, k_y, k_z) is the wave vector of holes.

Figure 2

Characterisation of the AHE and AMR effect, and SOT switching. a, Perpendicular magnetic field H_z dependence of the Hall resistance R_H and resistance R of (Ga_{0.94}Mn_{0.06})As at 40 K. b, Field-assisted SOT switching with $J \parallel [\bar{1}10]$ and $[110]$ in a 7-nm-thick (Ga_{0.94}Mn_{0.06})As thin film at 40 K, where the magnitude of H_{ext} is 300 Oe. c, d, Illustrations of the torques exerted by the spin component (" τ_{ST} "), the external field (" τ_{ext} ") and the anisotropy field (" τ_{an} ") with $J > 0$ for $J \parallel [\bar{1}10]$, $H_{ext} \parallel [\bar{1}10]$ (c) and $J \parallel [110]$, $H_{ext} \parallel [\bar{1}10]$ (d). " m " is in the y-z plane (c) and x-z plane (d). (Source data are provided as a Source Data file.)

Figure 3

V_g dependence of the ISD modulation and SOT switching with $J \parallel [\bar{1}10]$. a, ISD-VSD characteristics and b, ISD modulation ratio with the application of various gate voltages V_g of 0 V, ± 1 V, ± 5 V, ± 10 V, ± 15 V and ± 20 V at 40 K. VSD ranging from +0.1 V to -0.1 V was applied with a step of 0.001 V. c, Field-assisted SOT switching by applying V_g of 0 and ± 10 V. d, Plot of J_c obtained with various V_g in a 7-nm-thick (Ga $_{0.94}$ Mn $_{0.06}$)As thin film at 40 K. Here, $J \parallel [\bar{1}10]$ and $H_{ext} = 300$ Oe. In this measurement, we changed V_g in the order of 0 V $\rightarrow$ +5 V $\rightarrow$ -5 V $\rightarrow$ +10 V $\rightarrow$ -10 V $\rightarrow$ +15 V $\rightarrow$ -15 V $\rightarrow$ +20 V $\rightarrow$ -20 V. (Source data are provided as a Source Data file.)

Figure 4

Schematic illustrations of the interfacial electric field and the band structure. Schematic illustration of the gate voltage modulation of the interfacial electric field under a, $V_g = 0 \text{ V}$, b, $V_g > 0 \text{ V}$, and c, $V_g < 0 \text{ V}$. Schematic illustration of the band structure of Au/Cr/ AlO_x /(Ga,Mn)As under d, $V_g = 0 \text{ V}$, e, $V_g > 0 \text{ V}$, and f, $V_g < 0 \text{ V}$.

Figure 5

V_g dependence of SOT switching with $J // [\bar{1}10]$, H_c , and H_{an} . a, Field-assisted SOT switching with V_g of 0 and $\pm 10 \text{ V}$ in a 7-nm-thick (Ga_{0.94}Mn_{0.06})As thin film at 40 K. Here, $J // [110]$ and $H_{\text{ext}} = -300 \text{ Oe}$. b, Out-of-plane magnetic field H_z dependence and c, in-plane magnetic field H_y dependence of the Hall resistance R_H of (Ga_{0.94}Mn_{0.06})As with V_g of 0 and $\pm 10 \text{ V}$ at 40 K. The inset of (a) shows the coordinate relationship. (Source data are provided as a Source Data file.)

Supplementary Files

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