

Supplementary Information

Ultralow power spin-orbit torque magnetization switching induced by a non-epitaxial topological insulator on Si substrates

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1. Characterization of the CoTb(2.7)/Pt(1) stack

Figure S1(a) and S1(b) show the in-plane and out-of-plane magnetization curve of the CoTb(2.7)/Pt(1) stack measured by superconducting quantum interference devices (SQUID), which show the saturation of magnetization of 180 emu/cc and the magnetic anisotropy field of 1.6 kOe for CoTb. Figure S1(c) and S1(d) show the Hall resistance of a Hall bar of the stack as the function current density under $H_x = \pm 200$ Oe. We confirmed no SOT magnetization switching in the CoTb(2.7)/Pt(1) stack even at high $J \sim 6 \times 10^6$ A/cm² due to the very small $\theta_{\text{SH}}^{\text{eff}}$ of the Pt(1) layer. Indeed, the second harmonic measurement showed no signal of the spin orbit torque from the Pt(1) layer.

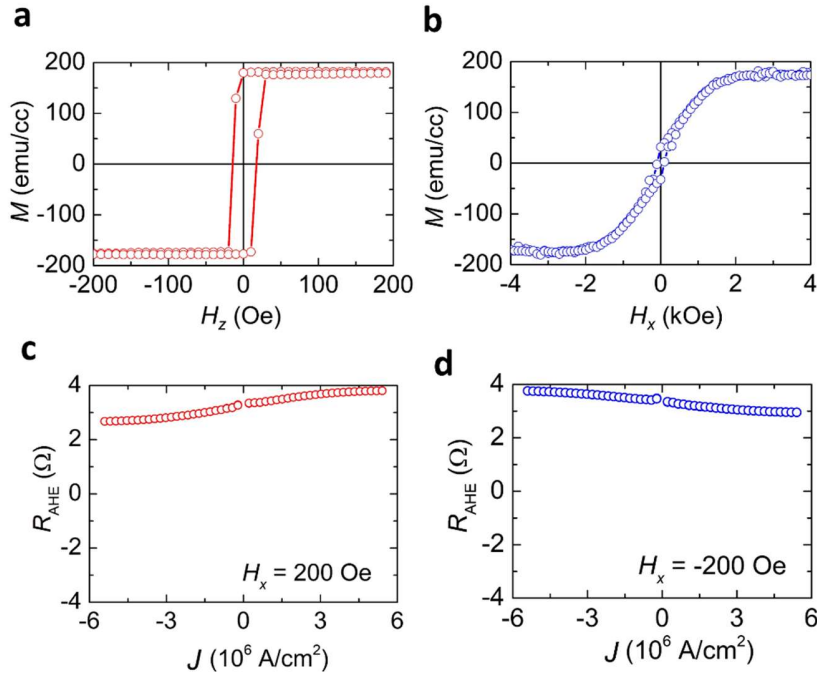


Figure S1. (a) Out-of-plane and (b) in-plane magnetization curve of the CoTb(2.7)/Pt(1) stack measured by superconducting quantum interference devices. (c) (d) Hall resistance of the stack as a function of the current density J under $H_x = \pm 200$ Oe.

2. Surface state conduction in the BiSb layers

We first determined the electrical conductivity of the BiSb layer at each temperature in sample A and sample B from the parallel resistor model of the CoTb/Pt and the BiSb layer. Then, we estimated the contribution of surface states and the bulk states to the total conductivity of the BiSb layer in sample A and sample B by using the parallel conduction model of the surface states and the bulk states. One distinct feature of BiSb from other well-known V-VI topological insulators such as Bi₂Se₃, Bi₂Te₃ or Sb₂Te₃, is that its bulk is always an intrinsic semiconductor with the Fermi level in the band gap. This is because Bi and Sb are in the same V-group, thus deviation of the composition or existence of anti-site defects does not result in any donors / acceptors that would generate free carriers and shift the Fermi level to the conduction band (as in the case of Bi₂Se₃ or Bi₂Te₃ due to anti-site Se/Te) or to the valence band (as in the case of Bi₂Te₃ or Sb₂Te₃ due to anti-site Bi/Sb). Therefore, the temperature dependence of the total electrical conductivity $\sigma(T)$ of BiSb is given by ⁴²

$$\sigma(T) = \frac{\sigma_{\text{Surface}}}{t} + \sigma_{\text{Bulk}} = \frac{\sigma_{\text{Surface}}}{t} + \sigma_0 \exp\left(-\frac{E_g}{2k_B T}\right) \quad (\text{S2.1})$$

where σ_{Surface} is the sheet conductivity of the surface states (both upper and lower surfaces), σ_{Bulk} is the bulk conductivity, t is the thickness of BiSb, and E_g is the effective bandgap of BiSb including the intrinsic band gap and the extrinsic bandgap due to quantum confinement.

Figure S2(a) shows the measured temperature dependence of the normalized resistivity of the 20 nm-thick BiSb layer in sample A and the 10 nm-thick BiSb layer in sample B, as well as the theoretical fitting using equation (S2.1). For the 20 nm-thick BiSb layer, the effective bandgap is $E_g \sim 126$ meV, which is already much larger than the intrinsic bandgap of 20 meV due to the quantum confinement effect. When the thickness is reduced to 10 nm, quantum confinement further increases the bandgap to $E_g \sim 200$ meV. We can also determine the surface contribution to

the total conductivity $\Gamma = \frac{I_{\text{Surface}}}{I_{\text{Surface}} + I_{\text{Bulk}}} = \frac{\sigma_{\text{Surface}}}{t} \bigg/ \left(\frac{\sigma_{\text{Surface}}}{t} + \sigma_{\text{Bulk}} \right)$, where I_{Surface} and I_{Bulk} are the current flowing into the surface states and the bulk states, respectively. Figure S2(b) shows Γ as a function of temperature. For the 20 nm-thick $\text{Bi}_{0.85}\text{Sb}_{0.15}$ layer, the surface state conduction accounts for 89% of the total current in the BiSb layer at room temperature. When the thickness is reduced to 10 nm, nearly all current flows into the surface of BiSb ($\Gamma \sim 97\%$) even at room temperature.

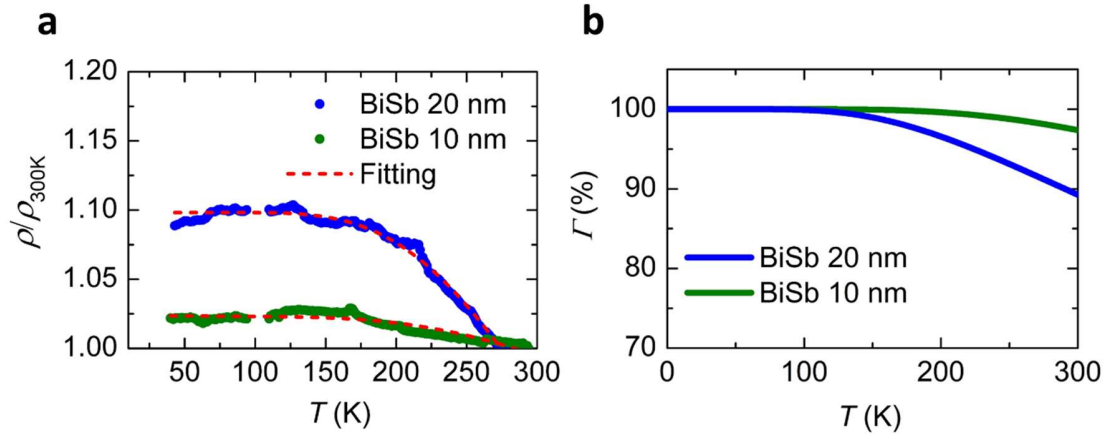


Figure S2. (a) Temperature dependence of the normalized resistivity of the 20 nm-thick $\text{Bi}_{0.85}\text{Sb}_{0.15}$ layer in sample A and the 10 nm-thick $\text{Bi}_{0.85}\text{Sb}_{0.15}$ layer in sample B. (b) Surface state contribution (both upper and lower surfaces) to the total conductivity Γ .

3. Dependence of the effective spin Hall angle $\theta_{\text{SH}}^{\text{eff}}$ on temperature in sample B

Figure S3(a)-S3(c) show the $H_{\text{AD}} - J^{\text{BiSb}}$ relationship measured at 320 K, 275 K, and 250 K for sample B. Figure 3(d) shows $\theta_{\text{SH}}^{\text{eff}}$ and M_{CoTb} as functions of temperature. $\theta_{\text{SH}}^{\text{eff}}$ increases in correlation with more surface conduction as temperatures decreases.

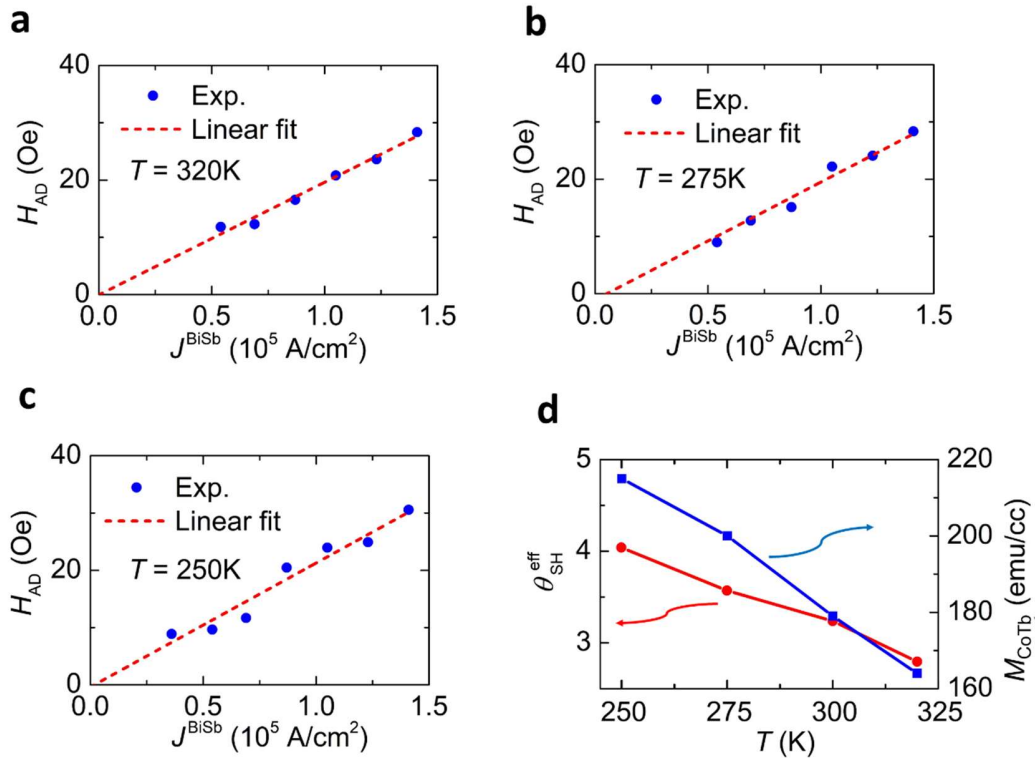


Figure S3. $H_{\text{AD}} - J^{\text{BiSb}}$ relationship in sample B measured at (a) $T = 320\text{K}$, (b) $T = 275\text{K}$, and (c) $T = 250\text{K}$. (d) $\theta_{\text{SH}}^{\text{eff}}$ (red) and magnetization M_{CoTb} (blue) as functions of temperature.