Supplementary Information for

Voltage-controlled skyrmion-based nanodevices for neuromorphic computing in a synthetic antiferromagnet

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S1. Influence of external electric field on the magnetic anisotropy constant

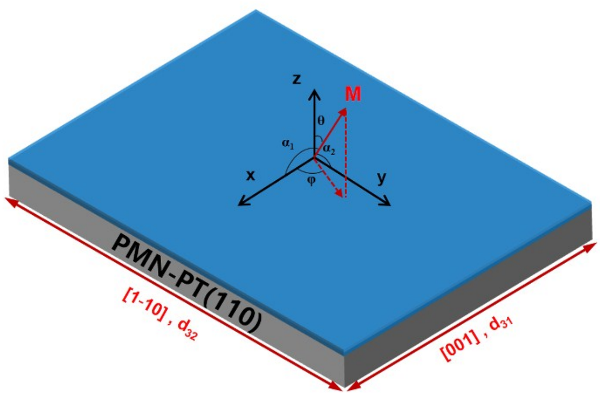

Fig. S1. Spatial angles of the magnetic moment of the ultrathin ferromagnetic film with perpendicular magnetic anisotropy on the PMN-PT(110) substrate

Variation of magnetic anisotropy energy under an external electric field for an ultrathin film with perpendicular magnetic anisotropy (PMA) is investigated quantitatively. Here, we consider an ultrathin film with PMA deposited on a PMN-PT(110) substrate (Fig. S1). The density of total magnetic anisotropy energy is:

$$F = K\sin^2\theta - \frac{3}{2}\lambda_S(\sigma_1\cos^2\alpha_1 + \sigma_2\cos^2\alpha_2) - \frac{1}{2}\mu_0 M_S^2\cos^2\theta \quad (1).$$

Here K, θ, $\alpha_{1(2)}$, $\sigma_{1(2)}$, λ_S, μ_0, M_S, are uniaxial anisotropy constant, polar angle, the angle between magnetization and $x(y)$ axis, the stress along $x(y)$ axis, the saturation magnetostriction coefficient, vacuum permeability, and the saturation magnetization.

In a spherical coordinate system, Eq. (1) is converted into:

$$F = K_{\mathrm{eff}} \sin^2 \theta$$

with

$$K_{\mathrm{eff}} = K - \frac{3}{2}\lambda_{\mathrm{S}}\sigma_1 + \frac{3}{2}\lambda_{\mathrm{S}}(\sigma_1 - \sigma_2)\sin^2 \varphi - \frac{1}{2}\mu_0 M_{\mathrm{S}}^2 \quad (2).$$

Usually, the relationship between stress and electric field strength (E) is nonlinear. However, when E is weaker than 0.5 kV/cm as indicated in the main text, $\sigma(E)$ is very close to a linear function [S1]:

$$\sigma_1 = \frac{Y}{1-\nu^2}(\nu d_{32} + d_{31})E$$
$$\sigma_2 = \frac{Y}{1-\nu^2}(\nu d_{31} + d_{32})E \quad (3).$$

Here Y and ν are the Young's Modulus and Poisson's ratio, respectively, of the ultrathin magnetic film layer, and d_{31} and d_{32} are the piezoelectric constants of the single-crystal PMN-PT substrate in the x ([001]) and y ([1−10]) directions, respectively. Plugging Eq. (3) into (2), we finally derive the relationship between K_{eff} and E as:

$$K_{\mathrm{eff}} = K - \frac{3}{2}\lambda_{\mathrm{S}}\sigma_1 + \frac{3}{2}\lambda_{\mathrm{S}}\frac{Y}{1+\nu}(d_{31} - d_{32})E\sin^2 \varphi - \frac{1}{2}\mu_0 M_{\mathrm{S}}^2 \quad (4).$$

Here Y and ν are 180 GPa and 0.3, and λ_S and M_S for Pt/Co (CoFeB) PMA film are 290 ppm (110 ppm) and 5.8×10^5 A/m (1.1×10^6 A/m) [S2-S5]. According to the experimental condition for electric field control of RKKY, the d_{31} and d_{32} for PMN-PT(110) are – 1800 pC/N and 900 pC/N, respectively [S6]. Based on these parameters, when $E > 0$, Eq. (4) is minimum for $\varphi = \pi/2$, and the K_{eff} is:

$$K_{\mathrm{eff}} = K - \frac{3}{2}\lambda_{\mathrm{S}}\sigma_2 - \frac{1}{2}\mu_0 M_{\mathrm{S}}^2 \quad (5).$$

On the other hand, when $E < 0$, Eq. (4) is minimum for $\varphi = 0$, and the K_{eff} is:

$$K_{\mathrm{eff}} = K - \frac{3}{2}\lambda_{\mathrm{S}}\sigma_1 - \frac{1}{2}\mu_0 M_{\mathrm{S}}^2 \quad (6).$$

In either case, when E is weaker than 0.5 kV/cm, the anisotropy constant contributed from stress is at the magnitude of $10^2 \sim 10^3$ J/m^3. The effective anisotropy constant for the demagnetization energy of Pt/Co (CoFeB) is 2.1×10^5 J/m^3 (7.6×10^5 J/m^3), and in general, the K for Pt/Co (CoFeB) is at the magnitude of 10^6 J/m^3 to ensure stable PMA. Therefore, the stress anisotropy energy contributes very little to the total magnetic anisotropy energy under such a weak electric field. Therefore, when E is weaker than 0.5 kV/cm as shown in the main text, it is reasonable that the variation of anisotropy constant can be neglected.

S2. Energy stability of skyrmion in the multilayer

The total energy for the stable skyrmion system was derived from the simulation. Two sorts of skyrmions were considered. In one case the magnetic moments inside the skyrmion are parallel to the magnetic moments in the lower layer (the ferromagnetic skyrmion (FM-Sky)), while it is on the contrary in the other case (the antiferromagnetic skyrmion (AFM-Sky)).

The results (Fig. S2) indicate that when the interlayer RKKY exchange coupling constant (J_{ex}) is between -1×10^{-7} J/m^2 and -3×10^{-6} J/m^2, the range of J_{ex} for the drastic changing of the radius of skyrmion, the energy for the stable FM-Sky is lower than that for the AFM-Sky. This proves that the FM-Sky-type skyrmion in the main text is stable in energy.

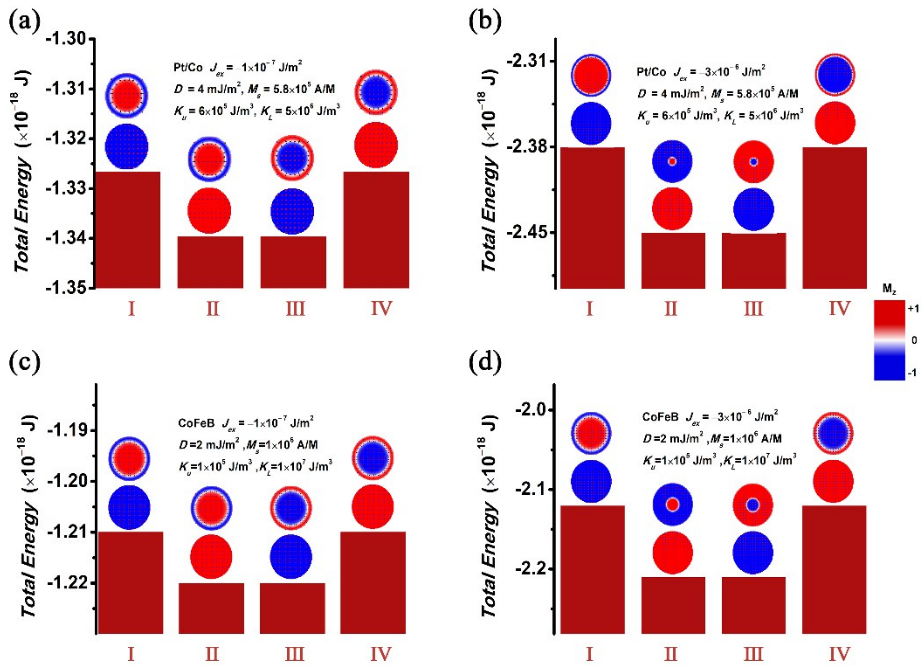

Fig. S2. Comparison of total energy between an FM-Sky and an AFM-Sky: (a) Pt/Co with $J_{ex} = -1 \times 10^{-7}$ J/m^2; (b) Pt/Co with $J_{ex} = -3 \times 10^{-6}$ J/m^2; (c) CoFeB with $J_{ex} = -1 \times 10^{-7}$ J/m^2; (d) CoFeB with $J_{ex} = -3 \times 10^{-6}$ J/m^2

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