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SUPPLEMENTARY INFORMATION

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Giant enhancement of spin accumulation and long-distance spin precession in metallic lateral spin valves

Nonlocal resistance in a lateral spin valve

When a magnetic field $\mathbf{B} = (0, 0, B_{\perp})$ is applied perpendicular to the plane of a spin injection and detection device consisting of a nonmagnetic metal (N) connected to the ferromagnets of the injector (F1) and the detector (F2), the injected spins in the N electrode precess around the z axis parallel to $\mathbf{B}$, as shown in Fig. 1. This precession changes the direction of accumulated spins by angle $\varphi = \omega_{\mathrm{L}} t$, where $\omega_{\mathrm{L}} = \gamma_e B_{\perp}$ is the Larmor frequency and $\gamma_e = 2\mu_{\mathrm{B}}/\hbar$ is the gyromagnetic ratio of conduction electrons in N, during the time t it takes electrons to travel from F1 to F2. When spin current I_1^s is injected into N from F1 at x = 0 and spin current I_2^s is ejected from N into F2 at $x = L$, the motion of the magnetization $\mathbf{m}$ due to the spin accumulation is governed by the Bloch-type equation[31]

$$\frac{\partial \mathbf{m}}{\partial t} = -\gamma_e \mathbf{m}\times\mathbf{B} - \frac{\mathbf{m}}{\tau_{\mathrm{sf}}} + D_{\mathrm{N}}\nabla^2\mathbf{m} + \frac{\hbar\gamma_e}{2e}\frac{I_1^s}{A_{\mathrm{N}}}\mathbf{e}_y\delta(x) - \frac{\hbar\gamma_e}{2e}\frac{I_2^s}{A_{\mathrm{N}}}\mathbf{e}_y\delta(x-L), \qquad \text{(S1)}$$

where τ_{sf} is the spin relaxation time, D_{N} is the spin diffusion constant, $\mathbf{e}_y$ is the unit vector in the y direction, and A_{N} is the cross- sectional area of N electrode. In magnetic fields smaller than the demagnetization field, the out-of-plane component m_z of magnetization is small and is disregarded for simplicity. The magnetization $\mathbf{m} = (m_x, m_y, 0)$ in the steady state $(\partial\mathbf{m}/\partial t = 0)$ of Eq. (S1) is given by the complex representation of magnetization in N

$$\tilde{m}(x) = m_y(x) + i m_x(x) = \frac{\hbar\gamma_e\lambda_\omega}{2eD_{\mathrm{N}}A_{\mathrm{N}}}\left[I_1^s e^{-|x|/\lambda_\omega} - I_2^s e^{-|x-L|/\lambda_\omega}\right], \qquad \text{(S2)}$$

with $\lambda_{\mathrm{N}} = \sqrt{D_{\mathrm{N}}\tau_{\mathrm{sf}}}$ and

$$\lambda_\omega = \frac{\lambda_{\mathrm{N}}}{\sqrt{1 + i\omega_{\mathrm{L}}\tau_{\mathrm{sf}}}}. \qquad \text{(S3)}$$

It is convenient to introduce a complex quantity $\delta\tilde{\mu}_{\mathrm{N}}(x) = \tilde{m}(x)/[2\mu_{\mathrm{B}}N(0)]$, the real part of which is related to the spin current density flowing in the x direction and polarized along the y direction

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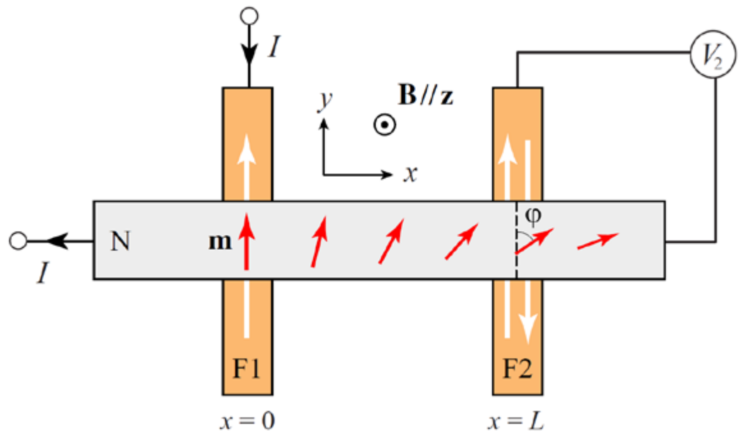

Figure S1 | Precession of accumulated spins in N where the magnetization **m** rotates by an angle φ during the travel of distance L between the injector F1 and the detector F2. The detected voltage V_2 probes the projection of **m** along the magnetization of F2.

$$j^s_{\rm N}(x) = -\frac{\hbar\gamma_e}{2e}\nabla m_y(x) = -\frac{\sigma_{\rm N}}{2e}\nabla\,{\rm Re}[2\delta\tilde{\mu}_{\rm N}(x)], \tag{S4}$$

where $\sigma_{\rm N} = \sigma^{\uparrow}_{\rm N} + \sigma^{\downarrow}_{\rm N}$ is the electrical conductivity of N electrode. The absolute value of $\delta\tilde{\mu}_{\rm N}(x)$ corresponds to the magnitude of the electrochemical potential (ECP) splitting $2\delta\mu_{\rm N} = \mu^{\uparrow}_{\rm N} - \mu^{\downarrow}_{\rm N}$ of the up and down spin electrons.

The spin transport in the presence of spin precession is described in terms of the complex ECP shift for up-spin and down-spin electrons

$$\delta\tilde{\mu}_{\rm N}(x) = \delta\tilde{\mu}^{\uparrow}_{\rm N}(x) = -\delta\tilde{\mu}^{\downarrow}_{\rm N}(x) = \frac{e}{2}\frac{\rho_{\rm N}\lambda_\omega}{A_{\rm N}}\left[I^s_1\,{\rm e}^{-|x|/\lambda_\omega} - I^s_2\,{\rm e}^{-|x-L|/\lambda_\omega}\right], \tag{S5}$$

where $\rho_{\rm N}$ is the electrical resistivity of N electrode, while the charge transport is described by the average ECP, $\bar{\mu}_{\rm N} = (\mu^{\uparrow}_{\rm N} + \mu^{\downarrow}_{\rm N})/2$, which takes $\bar{\mu}_{\rm N} = -(eI\rho_N/A_{\rm N})x$ for $x < 0$ and $\bar{\mu}_{\rm N} = 0$ (ground level of ECP) for $x > 0$. In Eq. (S5), the first term represents the increase of spin accumulation due to spin injection from F1, and the second term is the decrease due to spin absorption by F2. Note that, in the region of $x > 0$, the charge current ($j_{\rm N} = j^{\uparrow}_{\rm N} + j^{\downarrow}_{\rm N}$) is absent and only the spin current ($j^s_{\rm N} = j^{\uparrow}_{\rm N} - j^{\downarrow}_{\rm N}$) flows, implying the pure spin current is created in this region.

When the thicknesses of the F1 and F2 electrodes are much thicker than the spin diffusion length $\lambda_{\rm N}$, the solutions close to the interfaces may take the forms of vertical transport along

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the z direction:

$$\mu_{\mathrm{F1}}^{\sigma}(z)=\bar{\mu}_{\mathrm{F1}}-\frac{e\lambda_{\mathrm{F}}}{2\sigma_{\mathrm{F}}^{\sigma}A_{\mathrm{J}}}\left(I_1^s-P_{\mathrm{F}}I\right)e^{-z/\lambda_{\mathrm{F}}},\qquad \mu_{\mathrm{F2}}^{\sigma}(z)=\bar{\mu}_{\mathrm{F2}}-\frac{e\lambda_{\mathrm{F}}}{2\sigma_{\mathrm{F}}^{\sigma}A_{\mathrm{J}}}I_2^s e^{-z/\lambda_{\mathrm{F}}},\tag{S6}$$

where $\bar{\mu}_{\mathrm{F1}}=-(eI\rho_F/A_{\mathrm{J}})z+eV_1$ describes the charge current flow in F1, ρ_{F} is the electrical resistivity of F electrode, A_{J} is the contact area of the interface, λ_{F} is the spin-diffusion length of F electrode, $\bar{\mu}_{\mathrm{F2}}=eV_2$ takes a constant potential with no charge current in F2, V_1 and V_2 are the voltage drops across junctions 1 and 2, and $P_{\mathrm{F}}=|\sigma_{\mathrm{F}}^{\uparrow}-\sigma_{\mathrm{F}}^{\downarrow}|/(\sigma_{\mathrm{F}}^{\uparrow}+\sigma_{\mathrm{F}}^{\downarrow})$ is the spin polarization of F1 and F2.

The interfacial spin and charge currents across the junctions are described by using the current-perpendicular-to-plane giant magnetoresistance (CPP-GMR) theory[41]. In the presence of spin-dependent interface conductance $G_{\mathrm{I}i}^{\sigma}$ at junction i (i = 1, 2), the ECP changes discontinuously at the interface when the current flows across the junction. The spin-dependent interfacial current I_1^{σ} (I_2^{σ}) polarized along the y direction from F1 to N (from N to F2) is given by the ECP difference at the interface

$$I_1^{\sigma}=\frac{G_{\mathrm{I1}}^{\sigma}}{e}\left(\mu_{\mathrm{F1}}^{\sigma}(0)-\mathrm{Re}\left[\delta\tilde{\mu}_{\mathrm{N}}(0)\right]\right),\qquad I_2^{\sigma}=\frac{G_{\mathrm{I2}}^{\sigma}}{e}\left(\mathrm{Re}\left[\delta\tilde{\mu}_{\mathrm{N}}(L)\right]-\mu_{\mathrm{F2}}^{\sigma}(0)\right),\tag{S7}$$

where the distribution of the current is assumed to be uniform over the interface. The total charge and spin currents across the ith interface are $I_i=I_i^{\uparrow}+I_i^{\downarrow}$ $(I_1=I,\ I_2=0)$ and $I_i^s=I_i^{\uparrow}-I_i^{\downarrow}$. The above interfacial currents are applicable to junctions from tunneling to transparent regime.

The spin currents I_i^s and voltages V_i in Eqs. (S5) and (S6) are determined by the matching conditions that the spin and charge currents are continuous at the interfaces of junctions 1 and 2. Using the voltages, V_2^{P} and V_2^{AP}, detected by F2 in the parallel (P) and antiparallel (AP) alignments of magnetizations, the nonlocal resistance $R_S=V_2^{\mathrm{P}}/I=-V_2^{\mathrm{AP}}/I$ is calculated as

$$R_S=\frac{2R_{\mathrm{N}}^{\omega}\left[\frac{P_{\mathrm{I1}}}{1-P_{\mathrm{I1}}^2}\left(\frac{R_{\mathrm{I1}}}{R_{\mathrm{N}}^{\omega}}\right)+\frac{P_{\mathrm{F}}}{1-P_{\mathrm{F}}^2}\left(\frac{R_{\mathrm{F}}}{R_{\mathrm{N}}^{\omega}}\right)\right]\left[\frac{P_{\mathrm{I2}}}{1-P_{\mathrm{I2}}^2}\left(\frac{R_{\mathrm{I2}}}{R_{\mathrm{N}}^{\omega}}\right)+\left(\frac{P_{\mathrm{F}}}{1-P_{\mathrm{F}}^2}\right)\frac{R_{\mathrm{F}}}{R_{\mathrm{N}}^{\omega}}\right]\left(\frac{\mathrm{Re}[\lambda_{\omega}e^{-L/\lambda_{\omega}}]}{\mathrm{Re}[\lambda_{\omega}]}\right)}{\left[1+\frac{2}{1-P_{\mathrm{I1}}^2}\left(\frac{R_{\mathrm{I1}}}{R_{\mathrm{N}}^{\omega}}\right)+\frac{2}{1-P_{\mathrm{F}}^2}\left(\frac{R_{\mathrm{F}}}{R_{\mathrm{N}}^{\omega}}\right)\right]\left[1+\frac{2}{1-P_{\mathrm{I2}}^2}\left(\frac{R_{\mathrm{I2}}}{R_{\mathrm{N}}^{\omega}}\right)+\frac{2}{1-P_{\mathrm{F}}^2}\left(\frac{R_{\mathrm{F}}}{R_{\mathrm{N}}^{\omega}}\right)\right]-\left(\frac{\mathrm{Re}[\lambda_{\omega}e^{-L/\lambda_{\omega}}]}{\mathrm{Re}[\lambda_{\omega}]}\right)^2},\tag{S8}$$

where $R_{\mathrm{N}}^{\omega}=\mathrm{Re}[\rho_{\mathrm{N}}\lambda_{\omega}/A_{\mathrm{N}}]=R_{\mathrm{N}}\,\mathrm{Re}[\lambda_{\omega}/\lambda_{\mathrm{N}}]$ is the spin resistance of N electrode in the presence