Electric-field-induced ferromagnetic resonance excitation in an ultrathin ferromagnetic metal layer

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Supplementary information

1. FeCo thickness dependence of the perpendicular magnetic anisotropy

Figure S1 shows tunnel magnetoresistance curves of magnetic tunnel junctions with various FeCo thicknesses. External magnetic fields were applied perpendicular to the film plane. The thickness was varied from 0.54 to 0.77 nm. In this thickness range, the magnetic easy axis exists in the film plane, however, the magnetization can be directed to the out-of-plane by a relatively small perpendicular field of less than 0.5 T. Its magnetization process can be observed as the saturation behavior in the MR curve. To only focus on the change in the saturation field, the vertical axis was normalized by the maximum (at $H_{ex} = 0$ T) and minimum (at $H_{ex} = 0.5$ T) resistance values in this figure. Changes in the saturation field reflect the difference in the perpendicular anisotropy of the ultrathin FeCo layer depending on its thickness. The thinner sample tends to show the smaller saturation field; that is, it has the larger perpendicular magnetic anisotropy.

![Figure S1](image-url)

**Figure S1** FeCo thickness dependence of the normalized tunnel magnetoresistance curves measured under perpendicular magnetic fields.
2. Analytical expression of the homodyne detection signal intensity

Let us consider the macroscopic spin $\mathbf{S}$ of the ultrathin FeCo free layer that points in the $(\theta, \phi)$ direction in a spherical coordinate system (see Fig. S2, $\phi = 0$ in this figure). Definition of the axis is the same with the Fig. 3a, however, we introduce an in-plane rotation angle, $\phi_1$ for the spin of the top Fe (reference) layer, $\mathbf{S}_{\text{ref}}$ here. The unit vectors of the $\mathbf{S}$ and $\mathbf{S}_{\text{ref}}$ are given as $\hat{e}_z = (\cos \theta, 0, \sin \theta)$, and $\hat{e}_1 = (\cos \phi_1, \sin \phi_1, 0)$, respectively ($\hat{e}_2$ is expressed by $\hat{s}$ in the main text).

An external magnetic field, which is applied in the x-z plane, is expressed as

$$\hat{H}_{\text{ex}} = -H_{\text{ex}} (\cos \theta_H, 0, \sin \theta_H)$$

Here, we assigned a negative sign because it is assumed to be almost opposite to the spin $\mathbf{S}$.

The magnetic energy $U$ of this system is expressed as,

$$U = \frac{1}{2} \mu_0 M \hat{e}_z \cdot \left( \begin{array}{ccc} H_{\parallel, E} & 0 & 0 \\ 0 & H_{\parallel, H} & 0 \\ 0 & 0 & H_{d, \text{eff}} (V) \end{array} \right) \hat{e}_z + \mu_0 M \hat{e}_z \cdot \hat{H}_{\text{ex}}$$

$$= \frac{1}{2} \mu_0 M \begin{pmatrix} \cos \phi \cos \theta \\ \cos \phi \sin \theta \\ \sin \theta \end{pmatrix} \begin{pmatrix} H_{\parallel, E} & 0 & 0 \\ 0 & H_{\parallel, H} & 0 \\ 0 & 0 & H_{d, \text{eff}} (V) \end{pmatrix} \begin{pmatrix} \cos \phi \\ \cos \phi \sin \theta \\ \sin \theta \end{pmatrix} + \mu_0 M \begin{pmatrix} \cos \phi \cos \theta \\ \cos \phi \sin \theta \\ \sin \theta \end{pmatrix} \begin{pmatrix} H_{\text{ex}, x} \\ 0 \\ H_{\text{ex}, z} \end{pmatrix}$$

Here, $M$ is the saturation magnetization. The first term represents the magnetic anisotropy energy, and the second term expresses the Zeeman energy.

If we take into account an influence of spin-polarized tunneling current, the dynamics of the $\mathbf{S}$ is described by the following Landau-Lifshitz-Gilbert equation with the spin-transfer torque terms,

$$\frac{d\hat{e}_z}{dt} = \hat{e}_z \times \gamma \hat{H}_{\text{eff}} - \alpha \frac{1}{S} \hat{e}_z \times \frac{d\hat{e}_2}{dt} + \beta_{ST} \hat{e}_2 \times (\hat{e}_1 \times \hat{e}_2) + \beta_{FT} (\hat{e}_2 \times \hat{e}_1).$$

Here, $\beta_{ST} \hat{e}_2 \times (\hat{e}_1 \times \hat{e}_2)$ and $\beta_{FT} (\hat{e}_2 \times \hat{e}_1)$ are the in-plane spin-transfer torque and field-like torque, respectively. $\beta_{ST}$ and $\beta_{FT}$ are coefficients for each torque. Voltage effect can be included as the change in the $\hat{H}_{\text{eff}}$ as discussed in the main text.
Using the unit vectors in the $\theta$ and $\phi$ directions, $\vec{e}_\phi = (\sin \theta \cos \phi, \sin \theta \sin \phi, \cos \theta)$ and $\vec{e}_\theta = (-\sin \phi, \cos \phi, 0)$, the homodyne detection signal is expressed as follows.

$$
\langle \hat{V}_w(t) \rangle = - \frac{\eta R(\varphi)}{4 R_{at}} \frac{MR}{(\omega^2 - \omega_0^2) + \omega^2 \Delta \omega^2} \left( \cos \theta (\vec{e}_y \cdot \vec{e}_z) \left( \begin{pmatrix} \omega^2 \Delta \omega - \Omega_{12} (\omega^2 - \omega_0^2) \\ -\Omega_{22} (\omega^2 - \omega_0^2) \end{pmatrix} + \begin{pmatrix} \omega^2 \Delta \omega - \omega_0^2 \\ -\omega_0^2 \end{pmatrix} \right) \Omega_{11} \left( \begin{pmatrix} \omega^2 \Delta \omega + \omega_0^2 \\ -\omega_0^2 \end{pmatrix} \right) \right)
$$

$$
\times \frac{\partial}{\partial V} \left( \frac{1}{S \cos \theta} \left( \frac{\partial U}{\partial \theta} + \beta_{st} (\vec{e}_y \cdot \vec{e}_z) + \beta_{tr} (\vec{e}_y \cdot \vec{e}_z) \right) \right) V_r^2
$$

$$
= - \frac{\eta R(\varphi)}{4 R_{at}} \frac{MR}{(\omega^2 - \omega_0^2) + \omega^2 \Delta \omega^2} \left( \begin{pmatrix} \omega^2 \Delta \omega \\ -\omega^2 \end{pmatrix} \frac{1}{S \cos \theta} \frac{\partial U}{\partial \theta} (\vec{e}_y \cdot \vec{e}_z) + \begin{pmatrix} \frac{1}{S \cos \theta} \frac{\partial U}{\partial \phi} (\vec{e}_y \cdot \vec{e}_z) \\ \frac{1}{S \cos \theta} \frac{\partial U}{\partial \varphi} (\vec{e}_y \cdot \vec{e}_z) \end{pmatrix} \Omega_{11} \frac{\partial \Omega_{11}}{\partial \varphi} (\vec{e}_y \cdot \vec{e}_z) \frac{\partial U}{\partial \varphi} (\vec{e}_y \cdot \vec{e}_z) \right) V_r^2 \quad \ldots \ldots (S1).
$$

We assume that the relative angle of two ferromagnetic layers, $\varphi \approx \theta \approx \theta_t$, because a perpendicular component of the applied external field is relatively small, i.e. the tilt angle of the reference layer to the out-of-plane direction can be neglected in the present measurement condition.

Here, $\Omega$ matrix is given as follows.

$$
\hat{\Omega} = \begin{pmatrix}
\frac{\partial^2 U}{\partial \phi^2} & -\frac{1}{S \cos \theta} \frac{\partial^2 U}{\partial \theta \partial \phi} \\
\frac{1}{S \cos \theta} \frac{\partial^2 U}{\partial \theta \partial \phi} & \frac{1}{S \cos \theta} \frac{\partial^2 U}{\partial \theta^2} \cos \theta \frac{\partial \theta}{\partial \phi} \\
\frac{1}{S \cos \theta} \frac{\partial^2 U}{\partial \phi \partial \theta} & \frac{1}{S \cos \theta} \frac{\partial^2 U}{\partial \theta^2} \cos \theta \frac{\partial \theta}{\partial \phi}
\end{pmatrix}.
$$

If we only consider the voltage torque, Eq. S1 is simplified as follows,

$$
\langle \hat{V}_w(t) \rangle = - \frac{\eta R(\varphi)}{4 R_{at}} \frac{MR}{(\omega^2 - \omega_0^2) + \omega^2 \Delta \omega^2} \left( -\omega^2 \Delta \omega \sin \phi_i + (\omega^2 - \omega_0^2) \frac{\Omega_{11}}{S \cos \theta} \sin \theta \cos \phi_i \right) \frac{1}{S \cos \theta} \frac{\partial^2 U}{\partial \varphi} \frac{\partial U}{\partial \phi} V_r^2 \quad \ldots \ldots (S2).
$$

In our measurement condition, $\phi_i = 0$, only the dispersion structure is produced by the voltage torque.
Using the $\Omega_{11} = -\gamma S H_{d,\text{in-plane}} \cos^2 \theta - \gamma S H_{\text{ext}} \cos^2 \theta$ (here $H_{d,\text{in-plane}} = H_{/\text{H}} - H_{/\text{E}}$), and assume $\theta \approx \theta_\text{H}$, the peak signal intensity is given as follows (Eq. 1 in the main text),

$$V_{dc,\text{peak}} = \frac{\eta R(\phi)}{4 R_\text{AP}} M R \frac{1}{2 \Delta \omega} \frac{\gamma \phi H_\perp}{\partial V} \cos \theta \sin^2 \theta V_{\text{H}}^2.$$  

The peak intensity depends on the elevation angle $\theta$, with the form of $\cos \theta \sin^2 \theta$.

**Figure S2**  Spherical coordinate system of the macroscopic spin $\vec{S}$ of the ultrathin FeCo free layer, which points in the $(\theta, \phi)$ direction ($\phi = 0$ in this figure). The x and y axes are defined to be parallel to the in-plane magnetic easy (// FeCo[100]) and hard axis of the free layer. The z-axis is normal to the film plane. An external magnetic field is applied in the x-z plane, expressed as $\vec{H}_\text{ex} = -H_{\text{ex}} (\cos \theta_\text{H}, 0, \sin \theta_\text{H})$, which is almost opposite to the spin $\vec{S}$. $\phi_1$ is the in-plane rotation angle of the spin of the reference layer, $\vec{S}_\text{ref}$. $\vec{e}_\theta$ and $\vec{e}_\phi$ are the unit vectors toward $\theta$ and $\phi$ directions.

**3. In-plane field angle (rotation) dependence of the spectrum structure**

As we discussed in the main text, elevation angle dependence of the signal intensity provides clear evidence of the voltage-induced FMR excitation. An analysis of Eq. S1 also reveals another interesting point.

For the case of voltage torque, the spectrum structure depends on the direction of the reference layer, i.e. $\phi_1$. For example, under the assumption that the free layer is fixed in
the x-z plane ($\phi = 0$ degree), if $\hat{S}_{\text{ref}}$ is parallel to the x axis ($\phi_h = 0$ degree), the voltage torque produces a signal with the dispersion structure as observed in this experiment.

On the other hand, if $\hat{S}_{\text{ref}}$ is parallel to the y axis ($\phi_h = 90$ degrees), a signal with Lorentzian type structure will appear as expected from Eq. S2.

In contrast, field-like torque can only produce the dispersion type structure regardless of the angle $\phi_h$ as can be easily understood from Eq. S1. For the case of in-plane spin-transfer torque, we have both Lorentzian and dispersion terms; however, under the assumption of a large external magnetic field application, the dispersion part (the last term in Eq. S1) becomes negligibly small. Consequently, if the FMR excitation is induced by the spin-transfer torque or field-like torque, the spectrum structure does not change at $\phi_h = 0$ and 90 degrees. These features come from the fact that the spin-transfer and field-like torque depend on the direction of the $\hat{S}_{\text{ref}}$, while the voltage torque is determined by the applied voltage and the reference layer is used only for the detection.

To demonstrate this point, we investigated the $\phi_h$ dependence of the spectrum structure induced by both spin-transfer torque and voltage torque. Since the control of the reference layer direction is difficult in an actual experiment, we attempted to control the direction of the free layer magnetization by rotating the in-plane component of the external magnetic field ($\phi_H = 0$ and 90 degrees). The above discussion can be applied even in this situation by swapping the x and y axes.

For the spin-torque induced FMR experiment, we used a sputter deposited sample with the structure of Buffer / PtMn(15) / Co$_{70}$Fe$_{30}$(2.5) / Ru(0.85) / Co$_{50}$Fe$_{20}$B$_{20}$(3) / MgO(1)/Fe$_{80}$B$_{20}$(2)/MgO(1)/Ta(5) (thicknesses in nanometers). Cross-sectional shape of the element is circle with a diameter of 70 nm. Figure S3a and b show the results measured under the different external magnetic field angles of $\phi_H = 0$ and 90 degrees, respectively. The amplitude and the elevation angle of the external magnetic field were fixed at 0.2 T and 80 degrees. Since the in-plane field component is small (0.03 T) compared with the exchange bias field of the reference layer, we can assume that the reference layer is fixed in the x-axis, and only the spin of the free layer rotates depending on the direction of the applied external magnetic field. As expected from the theory, no clear change was observed in the spectrum structure. A slight shift of the resonance frequency may possibly originate from the influence of the stray field of the reference layer.

For the sample used to investigate the voltage effect, we cannot fix the reference
layer by an anti-ferromagnetic layer, so for this experiment, we fabricated a junction with a larger shape aspect ratio of the element, 0.2 × 0.8 μm², in order to make the reference layer magnetically hard. With keeping the tilt angle $\theta_H = 60$ degrees and $H_{ex} = 0.1$ T (the in-plane field component is about 0.05 T), homodyne detection signals were measured under rotation angles of $\phi_H = 0$ and 90 degrees. We found that the dispersion structure observed at $\phi_H = 0$ changed into the Lorentzian structure at $\phi_H = 90$ degree as shown in Fig. S3c and d. These results also can provide evidence of the voltage-induced FMR excitation.

![Diagram](image1)

**Figure S3** Rotation angle of the external magnetic field ($\phi_H$) dependence of the spectrum structure for the spin torque induced FMR ((a) $\phi_H = 0$ degrees, and (b) $\phi_H = 90$ degrees) and voltage induced FMR ((c) $\phi_H = 0$ degrees, and (d) $\phi_H = 90$ degrees). Elevation angles are $\theta_H = 80$ degrees for (a) and (b) and $\theta_H = 60$ degrees for (c) and (d), respectively.
The Eq. S1 predicts that the intensity of the Lorentzian type signal should be larger than the dispersion type; however, the opposite tendency was observed in the experiment. One possible origin of this discrepancy is the influence of the tilt angle of the Fe reference layer on the hard axis direction or magnetic domain formation due to an insufficient shape anisotropy field (judging from the magnetoresistance curve measured in the hard axis direction, the reference layer starts to rotate under the in-plane field of just around 0.05 T). To present a clear quantitative discussion, we need to prepare a junction with a tightly fixed reference layer, and perform further investigation.

4. Estimation of the efficiency, $\eta$

In order to discuss the intensity of the homodyne detection signal quantitatively, we have to take into account an influence of parasitic impedances in the sample, because there exists capacitance effect between the top and bottom electrode pads and inductance effect of the signal line. Figure S4a shows the equivalent circuit model of our system. Here, $R_0$ represents the resistance of the magnetic tunnel junction. $R_p$ and $C_p$ model capacitance effects and losses between the upper and lower electrodes around the sample. $Z_s$ is a pure inductor. $S_{11}$ parameter measurement using a network analyzer is useful to evaluate the parasitic impedances. $S_{11}$ is defined as $S_{11} = (Z - Z_0)/(Z + Z_0)$, where $Z$ and $Z_0$ are the impedance of the sample and characteristic impedance of the measurement system (50 $\Omega$). $Z$ is the sum of $Z_s$ and $Z_p$, here $Z_p$ consists of $R_0$, $R_p$ and $C_p$ (see Fig. S4). Figure S5a shows the fitting result of the $S_{11}$ measurement using this model for real (blue curve) and imaginary (red curve) parts. Transmission property of the rf signal was well reproduced by using the parameters of $R_0=9700$ $\Omega$, $R_p=6$ $\Omega$, $C_p=0.9$ pF, and $Z_s=100$ pF. By using the evaluated values of $Z_p$ and $Z_s$, the efficiency, $\eta$ in Eq. 1, is calculated as follows,

$$\eta = \frac{2Z_p}{Z_p + Z_s + Z_0} \quad \cdots (S4) .$$

Fig. S5b represents the estimated $\eta$. For example, at around 6 GHz, $\eta$ is about 1.
Figure S5 Analysis of $S_{11}$ properties and efficiency. \textbf{a}, Blue (red) dots represent experimental results of real (imaginary) parts and blue (red) lines represent the theoretical fitting results. \textbf{b}, Efficiency, $\eta$ calculated by Eq. S4.

It should be mentioned that these parasitic impedances also affect on the precession angle estimation. For this case, we need to multiply a precession efficiency factor, $\xi$ to the Eq. (2) in the main text, where, the $\xi$ is expressed as follows.

$$
\xi = \sqrt{2} \left| \frac{R_p Z_p + Z_s + Z_0}{Z_p R_0 + Z_0} \right| \quad\cdots\ (S5)
$$

Figure S6 shows the estimated $\xi$ for our sample. This factor is small in a low frequency range, e.g. at 1 GHz discussed in the main text, but in the high frequency range, we need to take into account this correction carefully.

Figure S6 Frequency dependence of the precession efficiency factor, $\xi$ for the quantitative evaluation of the FMR precession angle.