Supplementary Information

**Voltage-driven gigahertz frequency tuning of spin Hall nano-oscillators**

Jong-Guk Choi1†, Jaehyeon Park2†, Min-Gu Kang1, Doyoon Kim3, Jae-Sung Rieh3, Kyung-Jin Lee2, Kab-Jin Kim2★ and Byong-Guk Park1★

*1 Department of Materials Science and Engineering, KAIST, Daejeon 34141, Korea*

2 *Department of Physics, KAIST, Daejeon 34141, Korea*

3 *School of Electrical Engineering, Korea University, Seoul 02841, Korea*

**- Contents -**

**Note 1.** **ST-FMR spectra for various frequencies**

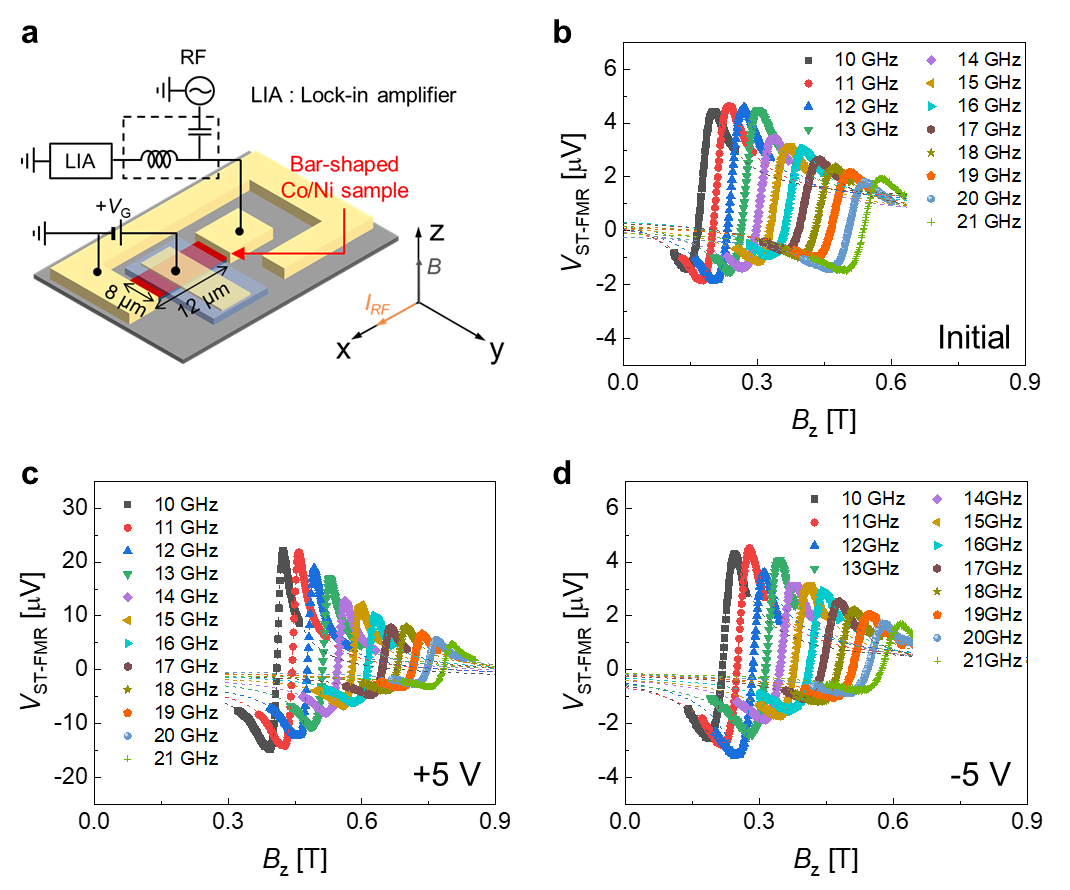
**Note 2. Voltage-driven frequency modulation in Co/Ni sample with a different thickness**

**Note 3. Gate voltage effect on the current-induced SOT**

**Note 4.** **Threshold current for current-induced magnetization auto-oscillation**

**Note1. ST-FMR spectra for various frequencies**

Figure S1a shows the schematic illustration of the ST-FMR measurement [S1, S2], of which details are discussed in the Method section of the main text. Figures S1b-S1d show the ST-FMR spectra of the Co/Ni sample with different ’s for various frequencies ranging from 10 to 21 GHz, measured while sweeping magnetic fields along the *z*-direction.

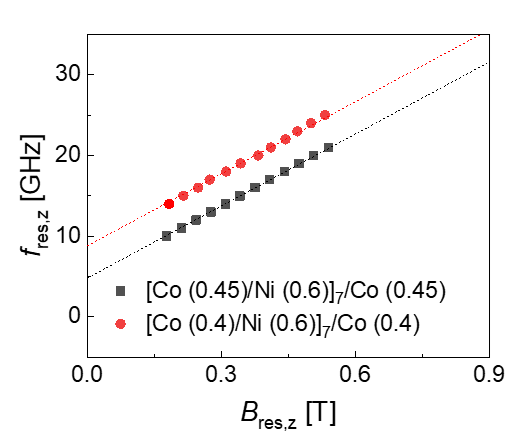
****

**Figure S1. ST-FMR measurement of Co/Ni sample for various frequencies. a,** Schematic diagram of the device structure of the ST-FMR measurement set-up. **b-d,** ST-FMR spectra of the Co/Ni sample for various frequencies ranging from 10 to 21 GHz with sequentially applied gate voltages = 0 V (initial) (b), = +5 V (c), and = -5 V (d). The dotted lines are the fitting curves based on Eq. (2) of the main text.

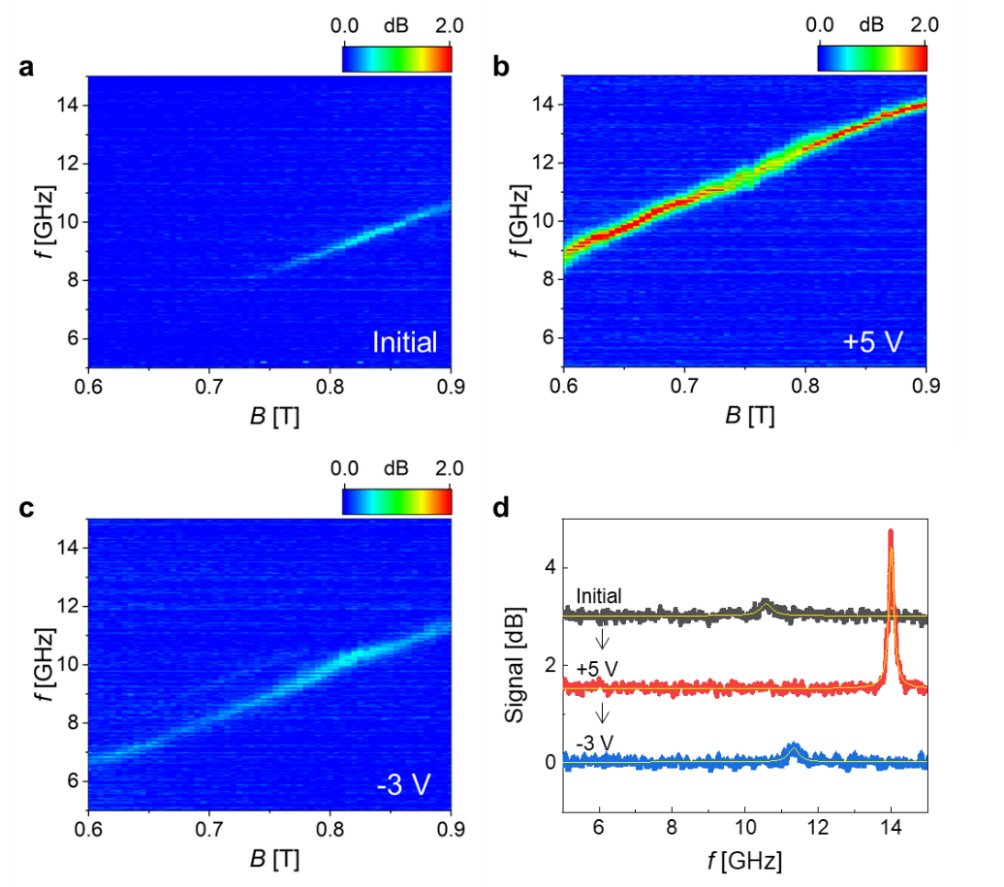
**Note 2. Voltage-driven frequency modulation in Co/Ni sample with a different thickness**

To show the reproducibility of the voltage-driven frequency modulation, we fabricated another Co/Ni device of Ta (3 nm)/Pt (5 nm)/[Co (0.4 nm)/Ni (0.6 nm)]7/Co (0.4 nm)/AlOx (2 nm), where a slightly thinner Co (0.4 nm) is used compared to the sample used in the main text has a [Ta (3 nm)/Pt (5 nm)/[Co (0.45 nm)/Ni (0.6 nm)]7/Co (0.45 nm)/AlOx (2 nm)]. We first check PMA of the sample using the ST-FMR measurement with the same procedure used in Fig. 2 of the main text. Figure S2 shows the resonance frequency () of ST-FMR spectra as a function of the resonance field () for two Co/Ni samples having different Co thicknesses. As the *y*-intercept indicates the PMA field () according to the Kittel formula [S3], demonstrating that the sample with a thinner Co has a stronger PMA.

We then fabricate an SHNO with a constriction width of 100 nm. The experimental procedure for the power spectral density (PSD) measurement is the same as used in Fig. 3 of the main text, except for a dc current () of 1.8 mA used. Figures S3a-S3c show the color plots of PSD as a function of a magnetic field (), where gate voltages of +5 V and -3V were sequentially applied. The auto-oscillation peak is clearly observed, and its frequency is increased by the positive voltage and restored by the subsequent negative voltage. Figure S3d shows the auto-oscillation spectra for a magnetic field of for different gate voltages, extracted from Figs. S3c-S3g. The frequency modulation of the sample with a thinner Co is about a few GHz, confirming the reproducibility of the voltage-driven frequency modulation of the SHNO.



**Figure S2. ST-FMR measurement.** Resonance frequency () of ST-FMR spectra as a function of the resonance field () for the samples of Ta (3 nm)/Pt (5 nm)/[Co (0.45 nm)/Ni (0.6 nm)]7/Co (0.45 nm)/AlOx (2 nm) (black squares) and Ta (3 nm)/Pt (5 nm)/[Co (0.4 nm)/Ni (0.6 nm)]7/Co (0.4 nm)/AlOx (2 nm) structures (red circles).

****

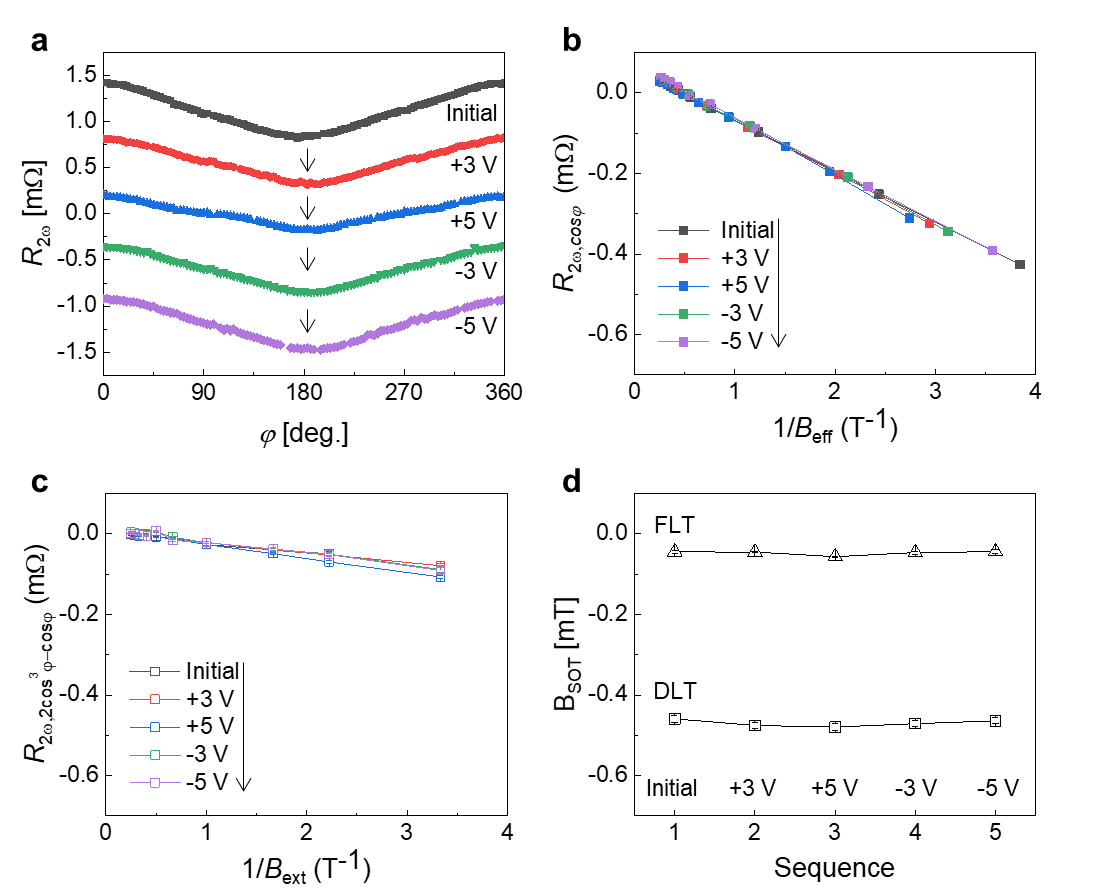
**Figure S3. Voltage-driven frequency modulation in SHNO of Ta (3 nm)/Pt (5 nm)/[Co (0.4 nm)/Ni (0.6 nm)]7/Co (0.4 nm)/AlOx (2 nm). a-c,** PSDs versus a magnetic field for sequentially applied gate voltages, = 0 V (initial state) (**a**), = +5 V (**b**), and = -3 V (**c**). = 1.8 mA. **d,** Auto-oscillation spectra for for different gate voltages, extracted from Figs. S3c-S3g. The yellow line is the Lorentz fit of the auto-oscillation spectra.

**Note 3. Gate voltage effect on the current-induced SOT**

We investigated the gate voltage effect on current-induced spin-orbit torque (SOT) using in-plane harmonic measurements. For the measurement, we fabricated a Hall bar device with a 10 μm × 10 μm cross using the Ta (3 nm)/Pt (5 nm)/[Co (0.45 nm)/Ni (0.6 nm)]7/Co (0.45 nm)/AlOx (2 nm) film. The first and second harmonic Hall resistance ( and ) were simultaneously measured with an a.c. current of 15 mA and a frequency of 11 Hz while rotating the sample (azimuthal angle *φ*) under an in-plane magnetic field (). The ranges from 0.3 T to 4.0 T, which is larger than the perpendicular magnetic anisotropy field ), so the magnetization is aligned in the magnetic field direction. The gate voltage was applied to the top electrode for 5 minutes at 150 ℃ before the measurement. Figure S4a shows the as a function of under a magnetic field of 0.6 T for various gate voltages. The can be expressed as [S4, S5],

, (2)

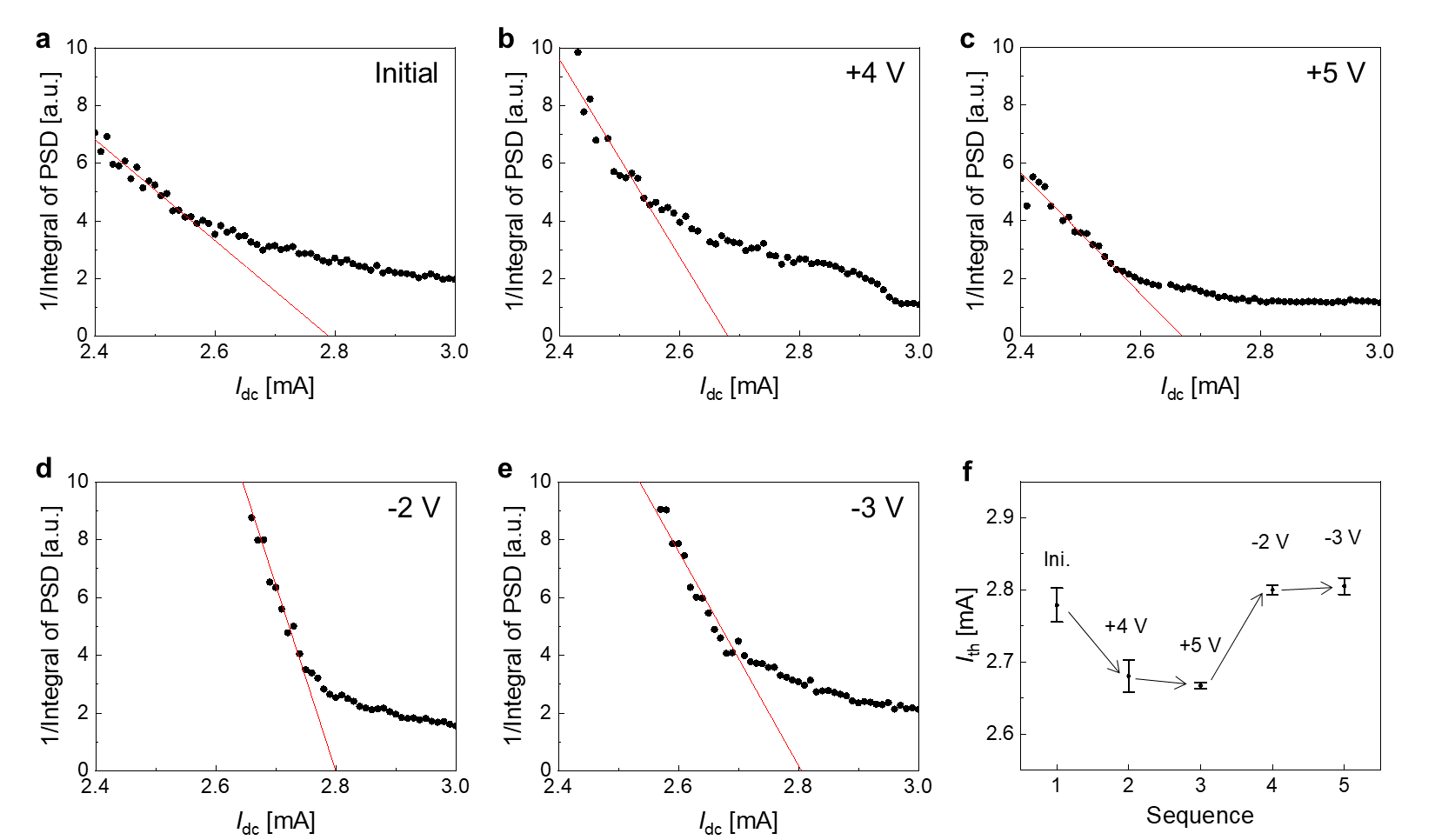
where , and are the anomalous Hall resistance, planar Hall resistance and thermal effect contribution, respectively; and are the damping-like effective field and field-like effective field including Oersted field, respectively; is the effective magnetic field (. Figures S4b and S4c show the magnetic field-dependence of the and () components of , respectively. Figure S4d demonstrates that the extracted and values of the sample, which are not changed by the gate voltage.



**Figure S4. Gate voltage effect on current-induced SOT. a,** Second-harmonic Hall resistance versus azimuthal angle under an in-plane magnetic field of 0.6 T for sequentially applied gate voltages. **b,** component of as a function of for sequentially applied gate voltages. **c,** () component of as a function of for sequentially applied gate voltages. The gate voltages were applied in the sequence indicated by the black arrows in Figs. S4a-S4c. **d,** The variation of the SOT-induced (black square) and (black triangle) values with sequentially applied gate voltages.

**Note 4. Threshold current for current-induced magnetization auto-oscillation**

We determine the threshold current () at which auto-oscillation begins to occur by a linear fit of the inverse of the PSD integral. Figures S5a-S5e show the (integral of PSD)-1 versus current for sequentially applied gate voltages, where *I*th is obtained by the *x*-intercept of the linear fit (solid red lines) [S6, S7]. Figure S4f displays the variation of with gate voltages, which is the same as Fig. 4f in the main text.



**Figure S5. Threshold current for current-induced magnetization auto-oscillation. a-e,** (integral of PSD)-1 as a function of current for sequentially applied gate voltages, Vg = 0V (initial) (**a**), = +4 V (**b**), = +5 V (**c**), = -2 V (**d**), and = -3 V (**e**). . **f,** according to the sequentially applied gate voltages, extracted from Figs. S5a-S5e.

**References**

1. Liu, L., Moriyama, T., Ralph, D. C. & Buhrman, R. A. Spin-torque ferromagnetic resonance induced by the spin Hall effect*. Phys. Rev. Lett.* **106**, 306601 (2011).
2. Kim, J. H. et al. Spin-orbit torques associated with ferrimagnetic order in Pt/GdFeCo/MgO layers. Sci. Rep. **8**, 6017 (2018).
3. Beaujour, J.-M., Ravelosona, D., Tudosa, I., Fullerton, E. E. & Kent, A. D. Ferromagnetic resonance linewidth in ultrathin films with perpendicular magnetic anisotropy. *Phys. Rev. B* **80**, 180415(R) (2009).
4. Hayashi, M., Kim, J., Yamanouchi, M. & Ohno, H. Quantitative characterization of the spin-orbit torque using harmonic Hall voltage measurements. *Phys. Rev. B* **89**, 144425 (2014).
5. Avci, C. O. *et al.* Interplay of spin-orbit torque and thermoelectric effects in ferromagnet/normal-metal bilayers. *Phys. Rev. B* **90**, 224427 (2014).
6. Tiberkevich, V., Slavin, A. & Kim, J. Von. Microwave power generated by a spin-torque oscillator in the presence of noise. *Appl. Phys. Lett*. **91**, 192506 (2007).
7. Awad, A. A., Houshang, A., Zahedinejad, M., Khymyn, R. & Åkerman, J. Width dependent auto-oscillating properties of constriction based spin Hall nano-oscillators. *Appl. Phys. Lett*. **116**, 232401 (2020).