

# Highly dose dependent damping-like spin-orbit torque efficiency in O-implanted Pt

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## ABSTRACT

Damping-like torque (DLT) arising from the spin Hall effect (SHE) in heavy metals and their alloys have been widely explored for applications in spin-orbit torque MRAM, auto-oscillations, spin waves and domain wall motion. In conventional materials, DLT efficiency is limited by intrinsic properties, while attaining strong spin-orbit coupling and higher spin-charge interconversion, with no compromise to electric properties, are the need of the hour. In this letter, we report more than 3.5 times increase in DLT efficiency,  $\theta_{DL}$ , of modified Pt-oxide, by employing a new approach of low energy 20 keV  $O^+$  ion implantation. The highest fluence of  $O^+$  implantation ( $1 \times 10^{17}$  ions  $cm^{-2}$ ) in Pt enhanced the DLT efficiency from 0.064 to 0.230 and improved the spin transmission for a smaller trade-off in the longitudinal resistivity ( $\rho_{Pt}$  to  $\rho_{Pt-Oxide}$ ) from 55.4 to 159.5  $\mu\Omega$ -cm respectively. The transverse spin Hall resistivity,  $\rho_{SH}$ , is found to be proportional to the square of the longitudinal resistivity i.e.  $\rho_{SH}^{imp} \propto \rho_{imp}^2$ , implying that the enhanced SHE in O-implanted Pt is due to a side-jumping mechanism. Further, no break in the two-fold and mirror symmetry of torques from O-implanted Pt allows the use of spin-torque ferromagnetic resonance based lineshape analysis to quantify such torques.

The existence of a strong spin-orbit coupling (SOC) in heavy metal (HM) has been instrumental in the research based on spin-based memory and logic devices<sup>1-3</sup>. The high SOC is utilized to generate large spin current density ( $J_S$ ) converted from charge current density ( $J_C$ ) in HM by means of phenomenological spin Hall effect (SHE)<sup>4</sup>. This spin current exerts a spin-orbit torque (SOT) on the magnetization of the adjacent ferromagnet (FM) layer attached to HM, which is one of the most important feature of SHE<sup>5,6</sup>. There are two basic components of SOT, first being the damping-like torque (DLT)  $\vec{\tau}_{DL} \propto \hat{m} \times (\hat{\sigma} \times \hat{m})$ , and second is the field-like torque (FLT)  $\vec{\tau}_{FL} \propto -(\hat{\sigma} \times \hat{m})$ <sup>7,8</sup>, where  $\hat{\sigma}$  is the unit vector along the spin polarization direction of the spin current, and  $\hat{m}$  is the magnetization unit vector. In fact, the former is more critical than the latter considering the intriguing applications that it provides in SOT-MRAM, logic operations, auto-oscillations, spin waves transmission and domain wall motion<sup>2,9-12</sup>.

The possibility of a strong DLT from the pre-existing heavy metals has attracted various groups to enhance it even further by alloying with not only metals such as PtSn alloy<sup>13</sup>, Zn and Ni-doped Pt<sup>14</sup>, Cu-Pt alloy<sup>15</sup>, Pt-Pd Alloy<sup>16</sup> Pt-Au alloy<sup>17</sup>, Pt-Hf dusting<sup>18,19</sup> but also the insertion of lighter elements like oxidation of Pt<sup>20</sup>, Ta<sup>21</sup>, W<sup>22</sup> and even recently adding nitrogen in Pt<sup>23</sup> have been shown as successful approaches to improve the charge-spin interconversion efficiency. However, for oxidation, most of the incorporation in these materials is attained from the natural process of sputtering which, if not controlled artificially such as alloying or other methods, may not be monotonic in DLT with varying concentrations<sup>21,23</sup>. Hence, in this respect, ion implantation, being an established artificial material engineering technique in the semiconductor industry is much more useful to incorporate non-metallic elements in heavy metals to enhance the DLT further. As a matter of fact, ion implantation or ion irradiation is already taking huge strides in the designing of future generation spintronic devices such as in spin-torque nano-oscillator using He<sup>+</sup>

irradiation<sup>24</sup>, interfacial hydrogen and oxygen ion manipulation at CoFeB/MgO based magnetic tunneling junction structures<sup>25</sup>, SOT driven multi-level switching in He<sup>+</sup> irradiated W/CoFeB/MgO hall bars<sup>26</sup> etc. To add, we had previously designed a new spin Hall material (SHM) by implanting low energy 12 keV sulfur ions in prototype Pt which demonstrated eight-times enhanced charge-to-spin interconversion efficiency and a very large spin Hall conductivity of  $\sim 8.32 \times 10^5 \left(\frac{\hbar}{2e}\right) \Omega^{-1} \text{m}^{-1}$  at 10 K, highest among reported Pt and its derivatives<sup>27</sup>.

In this paper, we report high DLT efficiency attained in modified Pt/NiFe, fabricated by non-metallic oxygen ion implantation, at a low energy of 20 keV with varying fluence/dose of  $2 \times 10^{16} - 1 \times 10^{17}$  ions  $\text{cm}^{-2}$ . We find consistent dose-dependent enhancement in DLT efficiency,  $\theta_{\text{DL}}$ , which is more than 250% increment and improved spin transmission estimated using room temperature spin-torque ferromagnetic resonance (ST-FMR)<sup>28</sup> based line shape analysis (spectral analysis) and linewidth analysis (modulation of damping) measurements. The monotonic increase in the impurity induced SH resistivity  $\rho_{\text{SH}}^{\text{imp}}$  is found to be proportional to the square of the longitudinal resistivity  $(\rho_{\text{Pt-Oxide}} - \rho_{\text{Pt}})^2$ , which reveals a side-jump scattering as the dominant mechanism of the enhanced SHE. In addition, no breaking of the mirror and two-fold symmetry in exerted spin-orbit torques shows the bulk-SHE origin. Compared with pristine Pt and other reported heavy metal oxide systems, O-implanted Pt/NiFe bilayer exhibited high  $\theta_{\text{DL}} = 0.230$  and spin mixing conductance  $g_{\text{eff}}^{\uparrow\downarrow} = 2.05 \times 10^{19} \text{ m}^{-2}$  with minor compromise in longitudinal resistivity. Our results open new avenues for ion-implantation as a novel guiding approach to design advanced materials that cater to low-power energy-efficient devices based on spin-orbitronics.

The multilayer stack of Pt (10 nm)/MgO(10 nm)/Al<sub>2</sub>O<sub>3</sub> (10 nm) on Si/SiO<sub>2</sub> substrates were deposited at room temperature using ultrahigh vacuum sputtering. Then, samples were implanted

with 20 keV O<sup>+</sup>-ion beam at a dose/fluence of  $2 \times 10^{16}$  ions cm<sup>-2</sup>,  $5 \times 10^{16}$  ions cm<sup>-2</sup>, and  $1 \times 10^{17}$  ions cm<sup>-2</sup> respectively. Then, oxide capping layers of MgO and Al<sub>2</sub>O<sub>3</sub> were removed by Ar<sup>+</sup> ion milling. One batch of samples was used for microstructure and surface morphology investigations. Supplementary figure S1(a-c) depict the microstructure images of respective O-implanted Pt surfaces using the scanning electron microscope (SEM) and affirm no substantial surface damage on any of the samples exposed to respective ion fluences of  $2 \times 10^{16}$  ions cm<sup>-2</sup>,  $5 \times 10^{16}$  ions cm<sup>-2</sup>, and  $1 \times 10^{17}$  ions cm<sup>-2</sup>. The average root-mean-square roughness was determined to be varying only from  $(0.76 - 0.96) \pm 0.01$  nm from respective topography image analysis. So, these results indicate that the optimized oxide capping layer provided the necessary protection and led to minimal surface agitation of 10 nm thick Pt films. We used the second batch to deposit top NiFe (5 nm) layer using ultrahigh vacuum sputtering immediately after the Ar<sup>+</sup>-milling process. Using photolithography, all three bilayer samples (named as N1, N2, and N3 with implanted doses of  $2 \times 10^{16}$  ions cm<sup>-2</sup>,  $5 \times 10^{16}$  ions cm<sup>-2</sup>, and  $1 \times 10^{17}$  ions cm<sup>-2</sup> respectively) were then patterned into  $10 \times 65 \mu\text{m}^2$  long micro strips. Finally, Ti (10nm)/Al (200 nm) electrodes were deposited using a lift-off process to design the co-planar waveguide structure for ST-FMR measurements as shown by optical image in Figure 1(a). Similarly, Hall bars were also fabricated to determine the longitudinal resistivity  $\rho_{\text{Pt-oxide}}$  of different O-dose implanted Pt without top NiFe layer.

First, to determine the DLT efficiency  $\theta_{\text{DL}}$ , we performed the lineshape analysis which uses the ratio of symmetric and antisymmetric components of ST-FMR spectra. The schematic of the ST-FMR measurement set-up is shown in Fig. 1(a). The device was excited with a microwave current  $I_{\text{rf}}$  of varying frequency  $f$  (5-11 GHz) with an applied power of  $P_{\text{app}} = 10$  dBm (10 mW). Simultaneously, an in-plane magnetic field  $H_{\text{ext}}$ , was swept from  $-2000$  Oe to  $+2000$  Oe at an angle of  $\phi = 45^\circ$  with respect to the device length. Thereby, flowing  $J_{\text{C}}$  in the O-implanted Pt layer

gets converted into  $J_s$  due to SHE and exerts a DLT on the magnetization of the adjacent FM layer. Meanwhile,  $h_{rf}$  arising from  $I_{rf}$  exerts an Oersted field torque (OFT) (Ampere's Law) and both the torques together drive magnetization precession in the NiFe layer. At FMR conditions, the mixing of periodic change in magnetoresistance  $\Delta R$  of NiFe and  $I_{rf}$  produces a rectified DC voltage  $V_{mix}$  which is detected using a lockin amplifier. Figure 1 (b-d) (i) shows the typical ST-FMR spectra for N1, N2, and N3, respectively. Note that, there is a reversal of symmetric component with the reverse in polarity of external magnetic field ( $H_{ext}$ ) which agrees with SHE symmetry and it also rules out the possibility of non-controlled relative phase between  $I_{rf}$  and  $h_{rf}$  that we retained in present measurements for a wide frequency range<sup>29</sup>. In addition, we also performed the calibration of  $P_{app}$  dependence of ST-FMR signal, provided in supplementary section S2. As the applied power increased from 0 dBm (1 mW) to 11 dBm (12.58 mW), the increased  $V_{mix}$  signal exhibited no change in the spectral linewidth and resonance field position which indicated that the precessing magnetization was in the linear regime at chosen power  $P_{app} = 10$  dBm (10mW). Next figure 1 (b-d) (ii) shows the ST-FMR spectrum obtained at  $f = 5$  GHz respectively for N1, N2, and N3 sample which are then subsequently fitted using Lorentzian function:

$$V_{mix} = SF_{sym}(H_{ext}) + AF_{asym}(H_{ext}), \quad (1)$$

where,  $F_{sym}(H_{ext}) = \frac{(\Delta H)^2}{(H_{ext} - H_0)^2 + (\Delta H)^2}$  is the symmetric component with weight S, and  $F_{asym}(H_{ext}) = \frac{\Delta H(H_{ext} - H_0)}{(H_{ext} - H_0)^2 + (\Delta H)^2}$  is the antisymmetric component with weight A and  $\Delta H$  and  $H_0$  are the half-width-at-half-maximum and resonance field of FMR spectra. While the symmetric component is proportional to DLT, the antisymmetric component is proportional to OFT. The  $V_{mix}$  spectrum is de-convoluted into symmetric and antisymmetric components for N1, N2, and N3

samples. It can be noticed that there is an increase in the symmetric component as the dosage of the oxygen ions increases 5 times.

Furthermore,  $\Delta H$  was plotted as a function of the applied frequency  $f$  in Fig. 2(a), for N1, N2, and N3. The Gilbert damping parameter  $\alpha$  was estimated using:

$$\Delta H = \Delta H_0 + \frac{2\pi\alpha}{\gamma} f, \quad (2)$$

where the first term  $\Delta H_0$  is the inhomogeneous linewidth broadening and  $\gamma$  is the gyromagnetic ratio. Here,  $\alpha$  was found to be increasing with dose for O-implanted Pt, N1 (0.0137), N2 (0.0153) and N3 (0.0164), unlike to Ta(O)/Py<sup>21</sup> which showed a small deviation around average  $\sim 0.01$  for different oxygen flow rates in Ta. Important to notice, that the inhomogeneous linewidth  $\Delta H_0 \sim 5$  Oe in all cases was found to very small which further confirmed the smooth and high quality of O-implanted Pt/NiFe interface fabrication. Dose dependent increase in  $\alpha$  clearly dictates the effect of enhanced DLT from O-implanted Pt. However, the additional spin relaxation due the presence of spin pumping cannot be ruled out here. Further, spin pumping also contributes to the symmetric component of the rectified  $V_{\text{mix}}$  signal in ST-FMR measurements<sup>30</sup>. Therefore, to confirm that the symmetric part is dominantly proportional to DLT here, the spin pumping contribution,  $V_{\text{sp}}$  (see supplementary section S3) was estimated and found it to be  $\sim 1$  % only. It showed that the spin current pumping back into the O-implanted Pt layer from precessing NiFe was negligible.

The effective magnetization  $4\pi M_{\text{eff}}$  values were then extracted by fitting the resonance frequency  $f$  as a function of  $H_0$  in Fig. 2(b) using the Kittel formula due to the negligibly small in-plane magnetic anisotropy in N1, N2 and N3 sample using:

$$f = \frac{\gamma}{2\pi} \sqrt{H_0(H_0 + 4\pi M_{\text{eff}})}, \quad (3)$$

The effective magnetization  $4\pi M_{\text{eff}}$  was calculated to be 0.799 T, 0.800 T and 0.811 T for N1, N2, and N3 respectively. We also evaluated the spin mixing conductance  $g_{\text{eff}}^{\uparrow\downarrow}$ <sup>30,31</sup> which is an important parameter describing the absorption of transverse spin current which is influenced by HM/FM interface. The  $g_{\text{eff}}^{\uparrow\downarrow}$  was estimated using the difference in linewidth  $\delta$  from the ST-FMR spectra ( $\delta = \Delta H_{\text{Pt-Oxide/NiFe}} - \Delta H_{\text{NiFe}}$ ) using  $g_{\text{eff}}^{\uparrow\downarrow} = \left(\frac{\gamma}{2\pi f}\right)\left(\frac{4\pi M_s t \delta}{g \mu_0 \mu_B}\right)$  where,  $g$  is the Landé  $g$  factor and  $\mu_B$  is the Bohr magneton. There is an enhancement of  $g_{\text{eff}}^{\uparrow\downarrow}$  with dose from  $1.53 \times 10^{19} \text{ m}^{-2}$  (N1) to  $2.05 \times 10^{19} \text{ m}^{-2}$  (N3). So, after confirming the insignificant contribution of spin pumping in symmetric component of the spectra and the enhancement of  $g_{\text{eff}}^{\uparrow\downarrow}$  with dose, we proceeded to quantify DLT efficiency  $\theta_{\text{DL}}$ , given as<sup>28</sup>:

$$\theta_{\text{DL}}^{\text{LS}} = \frac{S e \mu_0 M_s t d}{A \hbar} \sqrt{1 + \frac{4\pi M_{\text{eff}}}{H_0}}, \quad (4)$$

where,  $e$  is the electron charge,  $\mu_0$  is the permeability of free space,  $t$  is thickness of NiFe layer,  $d$  is thickness of Pt-Oxide layer,  $M_s$  is the saturation magnetization of NiFe. Figure 2(c) shows the calculated value of  $\theta_{\text{DL}}^{\text{LS}}$  of  $0.075 \pm 0.002$ ,  $0.107 \pm 0.002$  and  $0.230 \pm 0.003$  for N1, N2, and N3 respectively. This monotonic increase of  $\theta_{\text{DL}}^{\text{LS}}$  with O-dose shows that ion implantation could be a better alternative to incorporate nonmetallic elements in transition metals when compared to incorporating oxides/nitrides via sputtering<sup>21,23</sup>. In particular, the lineshape analysis performed here only at an angle of  $\phi = 45^\circ$  may not reveal the complete visualization of the generated spin-orbit torques<sup>32</sup> and therefore, angular ST-FMR measurements by varying the  $H_{\text{ext}}$  from  $\phi = 0^\circ$  to  $360^\circ$  is also crucial to analyze. Figure 2(d) shows that both S and A component are well fitted with expected  $\sin 2\phi \cos \phi$  behavior for highest dose of  $1 \times 10^{17} \text{ ions cm}^{-2}$  implanted Pt-Oxide/NiFe (N3) sample with no breaking of the mirror and two-fold symmetry<sup>33</sup>. It implies that lineshape analysis can be used for O-implanted Pt system which could give it an edge over other transition-metal



dichalcogenides<sup>33</sup>, where broken symmetry needs complex analysis to quantify such torques. Please refer supplementary section S4 to see the angular dependence of spin-orbit torques in other O-implanted Pt samples N1 and N2.

Second, to make the estimation of DLT efficiency,  $\theta_{DL}$ , more comprehensive, we employed an alternative approach of linewidth modulation as well since this method is free from spin pumping<sup>34</sup>. We used DC-biased ST-FMR technique<sup>28</sup> in which an additional DC current  $I_{dc}$  (+/-0.8mA) was also applied along with  $I_{rf}$  to modulate the linewidth  $\Delta H$  which either get increased or decreased based on the polarity of applied  $H_{ext}$ . The change in  $\Delta H$  can be seen in Fig. 3(a-c) for N1, N2 and N3 respectively which explicitly increased from  $\sim 1$  Oe (N1) to  $\sim 1.7$  Oe (N2) and finally to  $\sim 3$  Oe (N3). Further, using this change in  $\Delta H$ , we evaluated  $\theta_{DL}$  using the equation<sup>35</sup>:

$$\theta_{DL}^{LW} = \frac{\frac{2e}{\hbar}(H_0 + \frac{M_{eff}}{2})\mu_0 M_s t \left| \frac{\Delta\alpha_{eff}}{\Delta J_C} \right|}{\sin\phi}, \quad (5)$$

where,  $\Delta\alpha_{eff}$  is the effective change in damping due to  $I_{dc}$ . In accordance with the lineshape analysis, we observed a similar trend where  $\theta_{DL}^{LW}$  increased monotonically from  $0.074 \pm 0.021$  for N1 to  $0.106 \pm 0.022$  for N2 and then finally to  $0.231 \pm 0.024$  for N3. The DLT efficiency values obtained from the lineshape and linewidth modulation analyses along with estimated  $g_{eff}^{\uparrow\downarrow}$  and  $\rho_{Pt-Oxide}$  values are summarized in Table 1. Essentially by changing the impurity concentration i.e. different O-implantation dose in much wider range, we could obtain highly dose dependent DLT efficiency and therefore, it is more likely to be caused by an extrinsic mechanism.

As we understand there are two types of mechanism of extrinsic SHE namely, the skew scattering governed by explicit behavior of SH resistivity ( $\rho_{SH}^{imp}$ ) proportional to impurity induced resistivity ( $\rho_{imp}$ ), while, the side jumping scattering is associated with  $\rho_{SH}^{imp} \propto \rho_{imp}^2$  relationship

when impurities are the only source of resistivity<sup>36</sup>. We found a monotonic dependence of  $\theta_{DL}$  with the increase in longitudinal resistivity  $\rho_{Pt-Oxide}$  as concentration of  $O^+$  implantation increased as shown in Fig. 4, it hints towards the side-jump mechanism as the dominant origin of the enhanced SHE. To further probe the explicit contribution of impurities, we next focused on  $\rho_{SH}^{imp} = \rho_{SH}^{Pt-Oxide} - \rho_{SH}^{Pt}$  where  $\rho_{SH}^{Pt-Oxide}$  and  $\rho_{SH}^{Pt}$  are the SH resistivity of Pt-Oxide and pristine Pt which were estimated from respective charge-spin interconversion efficiency. See supplementary note S5 showing DLT efficiency obtained for pristine N0: Pt/NiFe sample. Here, the longitudinal resistivity from impurities  $\rho_{imp}$ , is identified using  $\rho_{imp} = \rho_{Pt-Oxide} - \rho_{Pt}$  and prominent signature of linear trend in  $\rho_{SH}^{imp}$  vs  $\rho_{imp}^2$  plot (see in inset of Fig. 4) establishes the extrinsic side-jump as the main origin of 250% enhanced SHE in O-implanted Pt with smaller trade-off in longitudinal resistivity from 55.4 to 159.5  $\mu\Omega\text{-cm}$ . For comparison, L. Yang et. al., obtained comparative  $\theta_{DL}$  of  $\sim -0.30$  with  $\rho_{Ta(O)}$  of  $\sim 200 \mu\Omega\text{-cm}^{21}$  and T.-Y. Chen et. al., obtained a  $\theta_{DL}$  of  $\sim -0.15$  with a  $\rho_{Ta(N)}$  of  $\sim 3000 \mu\Omega\text{-cm}^{37}$ , which highlights the present O-implanted Pt as a more promising material for spintronic applications using DLT.

In summary, we demonstrated a simple and effective implantation method that promotes the extrinsic spin Hall effect in a Pt layer to significantly enhance the room temperature damping-like-torque efficiency by more than 250%. The highest  $O^+$  ion implantation of  $1 \times 10^{17}$  ions  $\text{cm}^{-2}$  fluence at optimized energy of 20 keV in Pt led to very high damping-like-torque  $\theta_{DL} = 0.230$ , which is 3.5 times larger than the control sample of pristine Pt ( $\theta_{DL} = 0.064$ ). Both spectral line shape and modulation of damping in ST-FMR measurements unveiled the highly dose dependent increase in  $\theta_{DL}$  with improved spin transmission. Furthermore, linear fit of  $\rho_{SH}^{imp}$  vs  $\rho_{imp}^2$  plot, highlights the side-jump scattering as dominant mechanism of the enhanced SHE in our samples.

Our results emphasize on the ability to efficiently interconvert spin into electrical currents via custom engineered ion implantation.

See the supplementary material for the additional details of (1) Microstructure of O-implanted Pt, (2) Microwave power dependence (3) Spin pumping contribution, (4) Angular ST-FMR measurements and (5) Spin Hall angle of pristine Pt/NiFe sample.

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### **DATA AVAILABILITY**

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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Table 1:  $g_{\text{eff}}^{\uparrow\downarrow}$ ,  $\theta_{\text{DL}}^{\text{LS}}$ ,  $\theta_{\text{DL}}^{\text{LW}}$ , and  $\rho_{\text{Pt-oxide}}$  for different dose of Oxygen implantation.

O <sup>+</sup> implantation Dose	Sample	$g_{\text{eff}}^{\uparrow\downarrow}$ ( $10^{19} \text{ m}^{-2}$ )	$\theta_{\text{DL}}^{\text{LS}}$	$\theta_{\text{DL}}^{\text{LW}}$	$\rho_{\text{Pt-oxide}}$ ( $\mu\Omega\text{-cm}$ )
<b>Pristine Sample</b>	N0	1.25	0.064	0.066	55.4
<b><math>2 \times 10^{16} \text{ ions cm}^{-2}</math></b>	N1	1.53	0.075	0.074	84.9
<b><math>5 \times 10^{16} \text{ ions cm}^{-2}</math></b>	N2	1.80	0.108	0.106	117.0
<b><math>1 \times 10^{17} \text{ ions cm}^{-2}</math></b>	N3	2.05	0.230	0.231	159.5

## Figure Captions:

**Figure 1.** (a) Schematic showing ST-FMR measurement technique with optical image of micro-device and detection principle in bilayer thin film. STFMR spectra plotted for  $f = 5$  to 11 GHz range obtained from different O-implanted (b-i) N1, (c-i) N2, and (d-i) N3 samples. Deconvolution fitting of  $V_{\text{mix}}$  measured at  $f = 5$  GHz into symmetric and antisymmetric components displayed by green and violet solid line respectively for (b-ii) N1, (c-ii) N2, and (d-ii) N3 sample shows continuous increase in DLT.

**Figure 2.** (a)  $\Delta H$  vs  $f$  (with solid lines as linear fit), (b)  $f$  vs  $H_0$  (with solid lines as Kittel equation fit) and (c) Frequency invariant  $\theta_{\text{DL}}^{\text{LS}}$  obtained for N1, N2 and N3. The dashed line represents the average value. (d) Angular dependence of symmetric (S) and antisymmetric (A) components in ST-FMR spectra for N3 for  $f = 5$  GHz with solid lines fitted by  $\sin 2\phi \cos \phi$ . The error bars show the standard error in from the Lorentzian function fitting.

**Figure 3.** Varying  $\Delta H$  plotted as a function of  $I_{\text{dc}}$  (+/- 0.8 mA) for  $f = 5$  GHz with slope determined from linear fit (solid lines) for (a) N1, (b) N2, and (c) N3. The error bar is showing the standard error in the mean value of  $\Delta H$  obtained after Lorentzian fitting the STFMR signal using equation (1).

**Figure 4.**  $\theta_{\text{DL}}$  as a function of  $\rho_{\text{Pt-oxide}}$  obtained for N0 (Pristine Pt/NiFe), N1, N2, N3. The error bars explain the maximum possible deviation in respective values. Inset shows  $\rho_{\text{SH}}^{\text{imp}}$  vs  $\rho_{\text{imp}}^2$  behavior with solid black line as a linear fit.



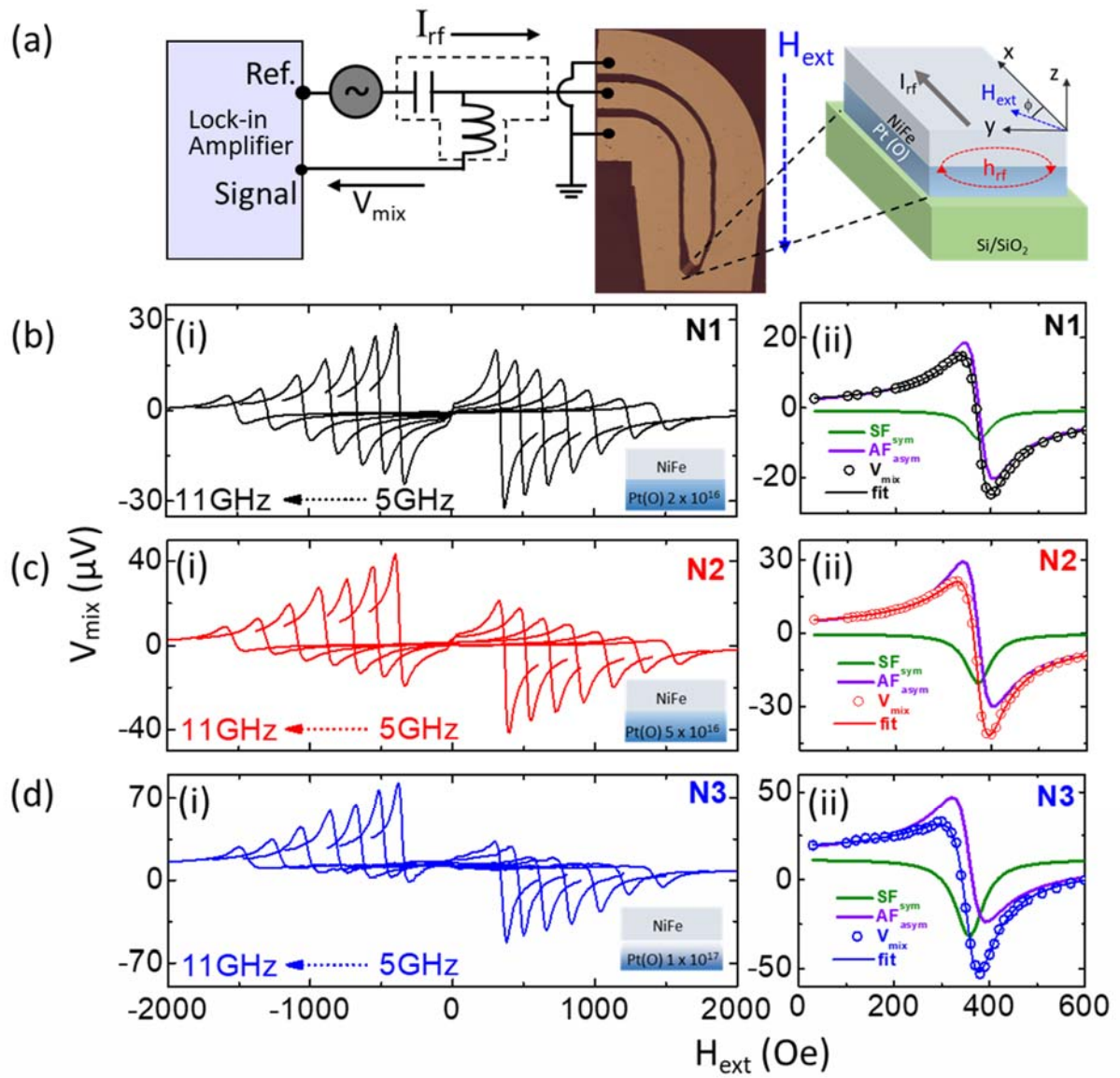


Fig. 1, U. Shashank et al.

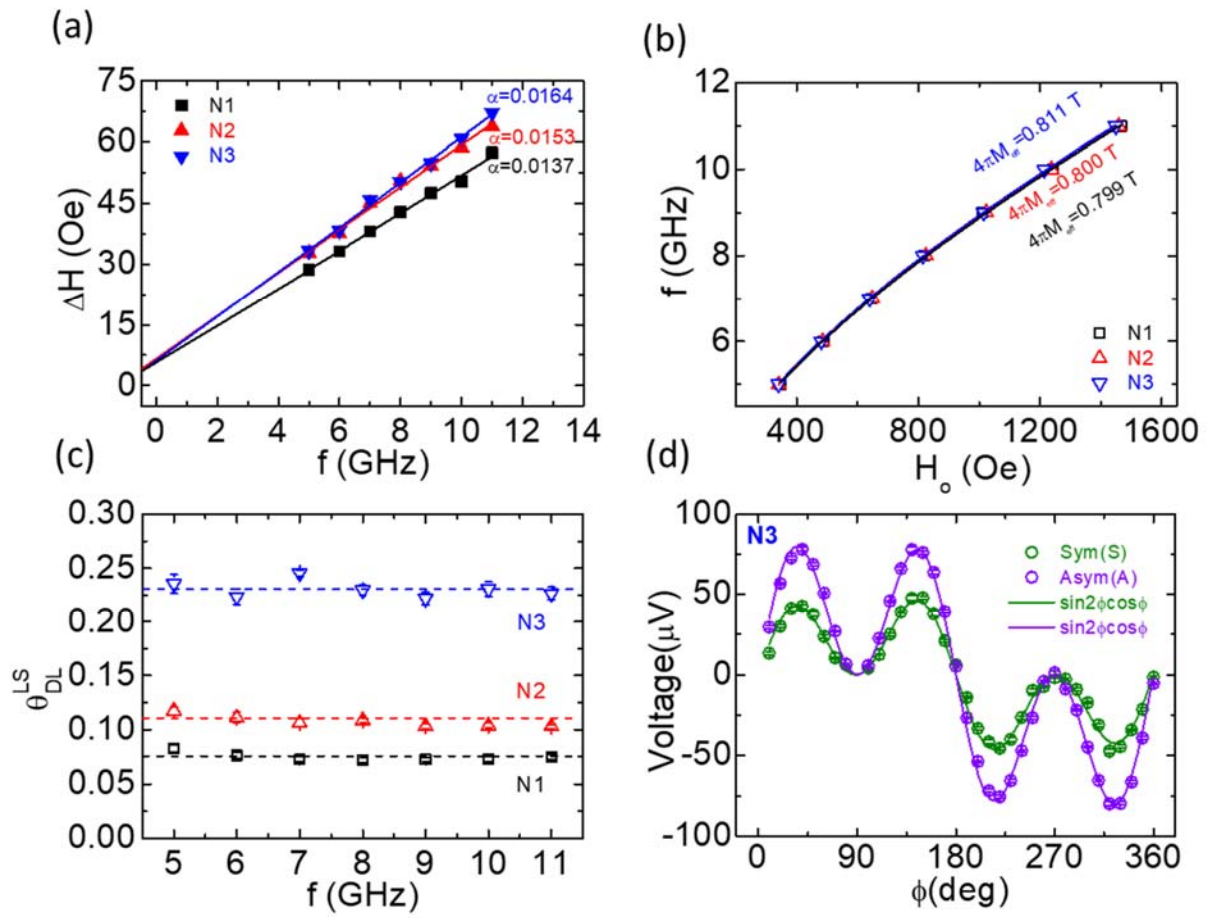


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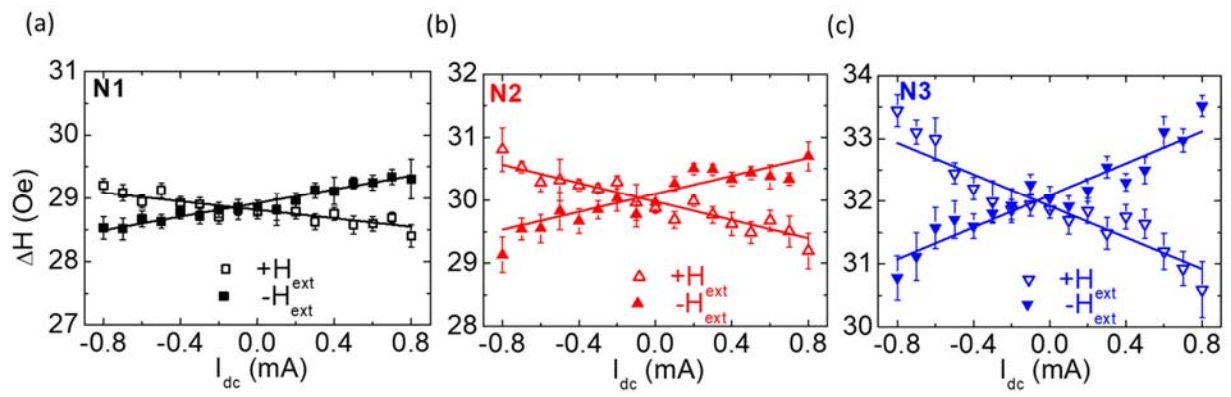


Fig. 3, U. Shashank et al.

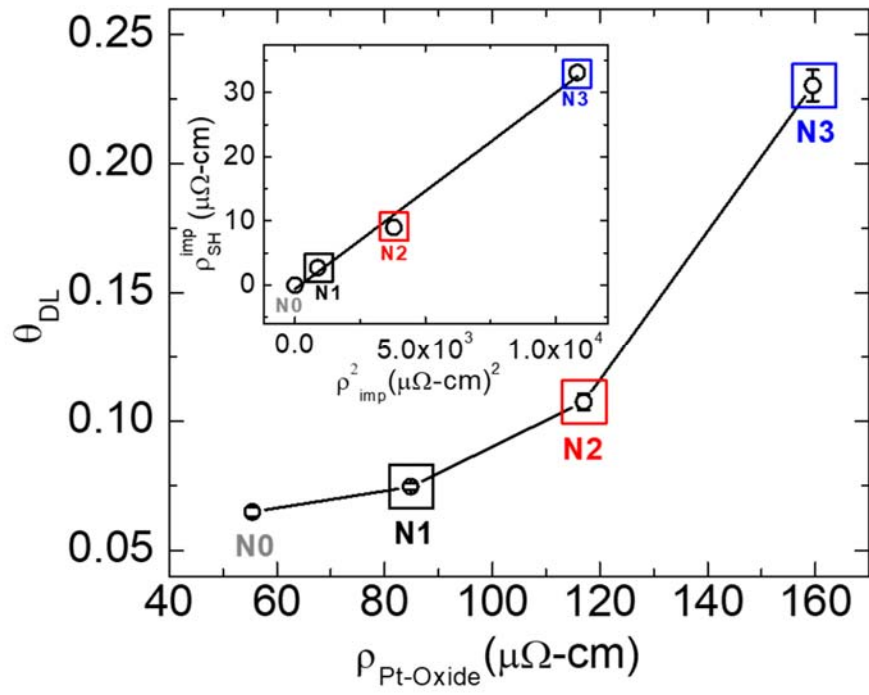


Fig. 4, U. Shashank et al.

## **Supplementary Information**

### **Highly dose-dependent damping-like spin-orbit torque efficiency in O-implanted Pt**

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**Contents:**

**S1: Microstructure for different doses of O-implanted Pt after removal of capping layers**

**S2: Microwave power dependence**

**S3: Role of Spin pumping contribution in the symmetric component of ST-FMR signal**

**S4: Angular dependent ST-FMR measurements**

**S5: ST-FMR measurements for pristine Pt/NiFe**

**S1: Microstructure for different doses of O-implanted Pt after removal of capping layers**

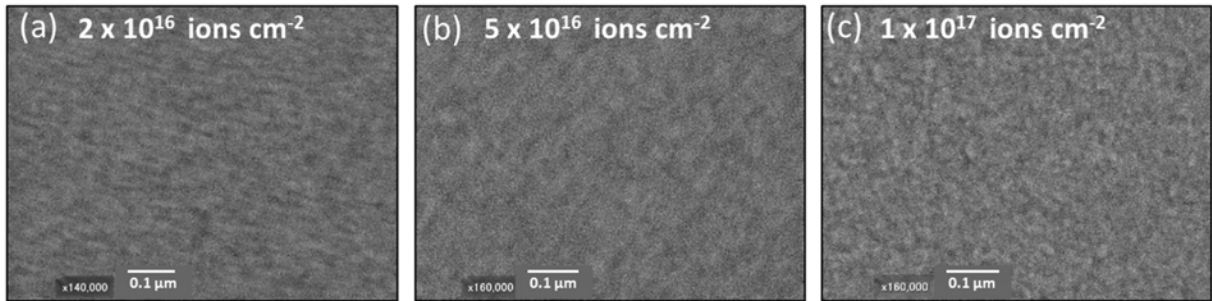


Figure S1: Microstructure for different doses of O-implanted Pt, (a)  $2 \times 10^{16}$  ions  $\text{cm}^{-2}$ , (b)  $5 \times 10^{16}$  ions  $\text{cm}^{-2}$ , and (c)  $1 \times 10^{17}$  ions  $\text{cm}^{-2}$  respectively, after removal of capping layers ( $\text{MgO}/\text{Al}_2\text{O}_3$ ).

## S2: Microwave power dependence

We used a nominal power of  $P_{\text{app}} = 10$  dBm (10 mW) in our ST-FMR measurements. To understand if this power is not large enough to induce nonlinear FMR in NiFe, we focused on power dependent ST-FMR measurements<sup>1</sup> by measuring  $V_{\text{mix}}$  at  $f = 5$  GHz in wide range of  $P_{\text{app}}$  (1-12.58 mW). Figure S2 (a) shows  $V_{\text{mix}}$  for one of the O-implanted Pt samples exhibiting no change in  $\Delta H$  and  $H_0$  with increase in  $P_{\text{app}}$ . Further, the extracted weight S and A (green and violet symbols) are plotted as a function of power in Fig. S2 (b) with a linear fit (solid line). We can infer that the precessing magnetization is in the linear regime at  $P_{\text{app}} = 10$  dBm (10mW) (red box). Additionally, we plotted the ratio of weight S/A as a function of power and found it to be invariant in this applied power range as shown in Fig. S2 (c).

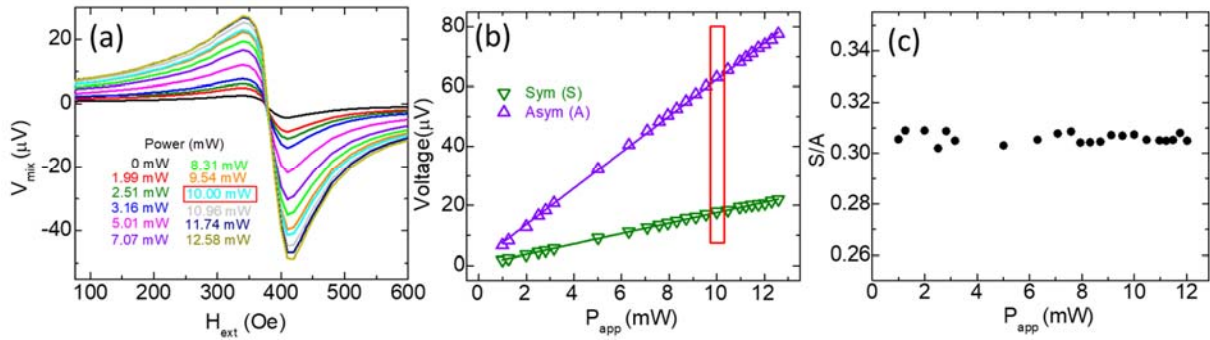


Figure S2: (a) Obtained rectified voltage spectra  $V_{\text{mix}}$  at  $f = 5$  GHz for power 1-12.58 mW for one of the O-implanted Pt sample. (b) Extracted S and A (with solid lines as linear fit) and (c) invariant S/A as a function of power.



### S3: Role of Spin pumping contribution in the symmetric component of ST-FMR signal

The symmetric component in ST-FMR spectra must be analyzed precisely for weak resonance signal since it might originate not only from DLT but also by spin pumping in which a precessing ferromagnet (here NiFe) pumps a spin current back into the Pt-Oxide. This spin current might get converted back to voltage output by inverse spin-to-charge conversion. Moreover, the spin pumping contribution has same  $\sin 2\phi \cos \phi$  dependence and so angular dependent ST-FMR cannot be used to differentiate these two effects.

Hence, the role of spin pumping can be assessed by calculating spin pumping contribution which can be expressed as  $V_{SP} = \frac{\theta_{DL} l \lambda_{sd}}{d \sigma_{Pt(O)} + t \sigma_{NiFe}} \tanh\left(\frac{d}{2\lambda_{sd}}\right) \left(\frac{2e}{\hbar}\right) J_s \sin \phi^1$  where,  $\theta_{DL}$  is DLT efficiency of Pt-Oxide,  $l$  is the length of device,  $\lambda_{sd}$  is the spin diffusion length in the Pt-Oxide,  $d$  and  $\sigma_{Pt(O)}$  are thickness and conductivity of Pt-Oxide,  $t$  and  $\sigma_{NiFe}$  are the thickness and conductivity of NiFe,  $e$  is the electronic charge,  $\hbar$  is the reduced Planck constant,  $\phi$  is the angle between external magnetic field and microwave current ( $45^\circ$  for this case),  $J_s$  is the spin pumping current into Pt-Oxide due to precessing NiFe given as  $J_s = \frac{\hbar}{2} f \sin^2 \theta_c g_{eff}^{\uparrow\downarrow}$  where,  $f$  is frequency,  $g_{eff}^{\uparrow\downarrow}$  is the spin mixing conductance and  $\theta_c = \frac{1}{dR/d\phi} \frac{2}{I_{rf}} \sqrt{S^2 + A^2}$  in which  $S$  and  $A$  are the weight factors for symmetric and antisymmetric components respectively,  $dR/d\phi$  is obtained from AMR,  $I_{rf}$  is the amount of current in device. For e.g.,  $V_{SP}$  is found to be  $0.05 \mu V$  as compared to  $S = 8.15 \mu V$  which is less than 1% ( $\sim 0.65\%$ ) at 5 GHz for N1;  $V_{SP}$  is found to be  $0.11 \mu V$  as compared to  $S = 20.2 \mu V$  for N2 ( $\sim 0.56\%$ ) and  $V_{SP}$  is found to be  $0.23 \mu V$  as compared to  $S = 43.67 \mu V$  for N3 ( $\sim 0.53\%$ ). Therefore, spin pumping contribution does not play a significant role in the symmetric component of present ST-FMR signal.

#### S4: Angular dependent ST-FMR measurements

The careful analysis of ST-FMR lineshape is a prerequisite to quantify the DLT as there may be latent effects such as effective field with different spin polarization, ambiguous effective field orientation, apart from the conventional spin Hall effect<sup>2</sup>. This may overlap with Symmetric and Antisymmetric signal of ST-FMR spectra. Hence, we performed angular dependent ST-FMR measurements to rule out these possibilities in our system by varying the direction of  $H_{\text{ext}}$  with respect to device length ( $I_{\text{rf}}$ ) from  $0^\circ$  to  $360^\circ$ . The symmetric (S) and antisymmetric(A) components can be fitted with  $\sin 2\phi \cos \phi$  where,  $\sin 2\phi$  is from AMR, whereas  $\cos \phi$  is from DLT and OFT for S and A respectively.

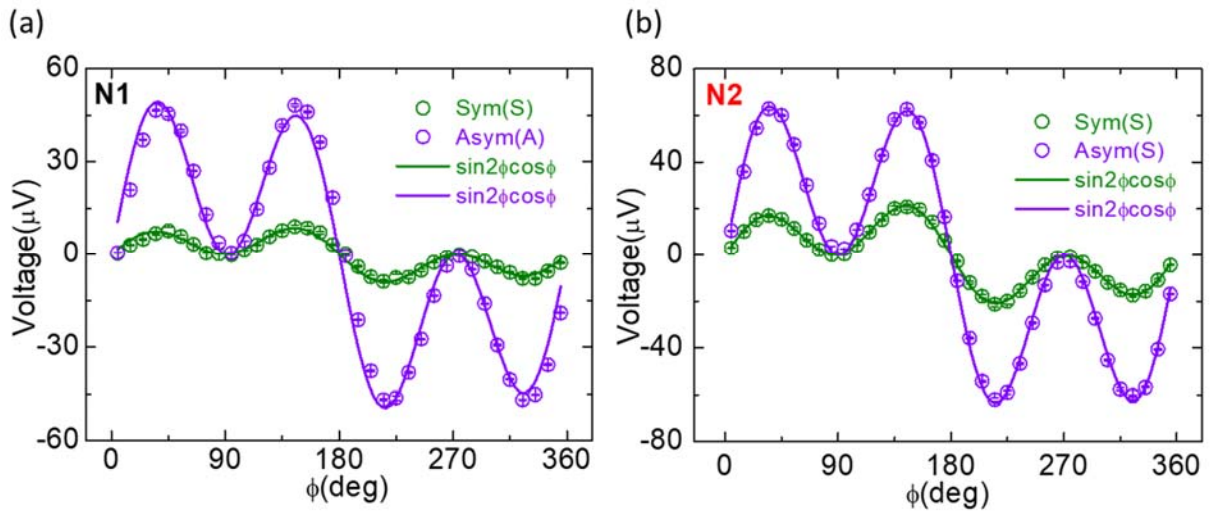


Figure S4: Angular dependence of symmetric and antisymmetric component measured at  $f = 5$  GHz for (a) N1 and (b) N2 sample.

### S5: Spin Hall angle of pristine Pt/NiFe sample

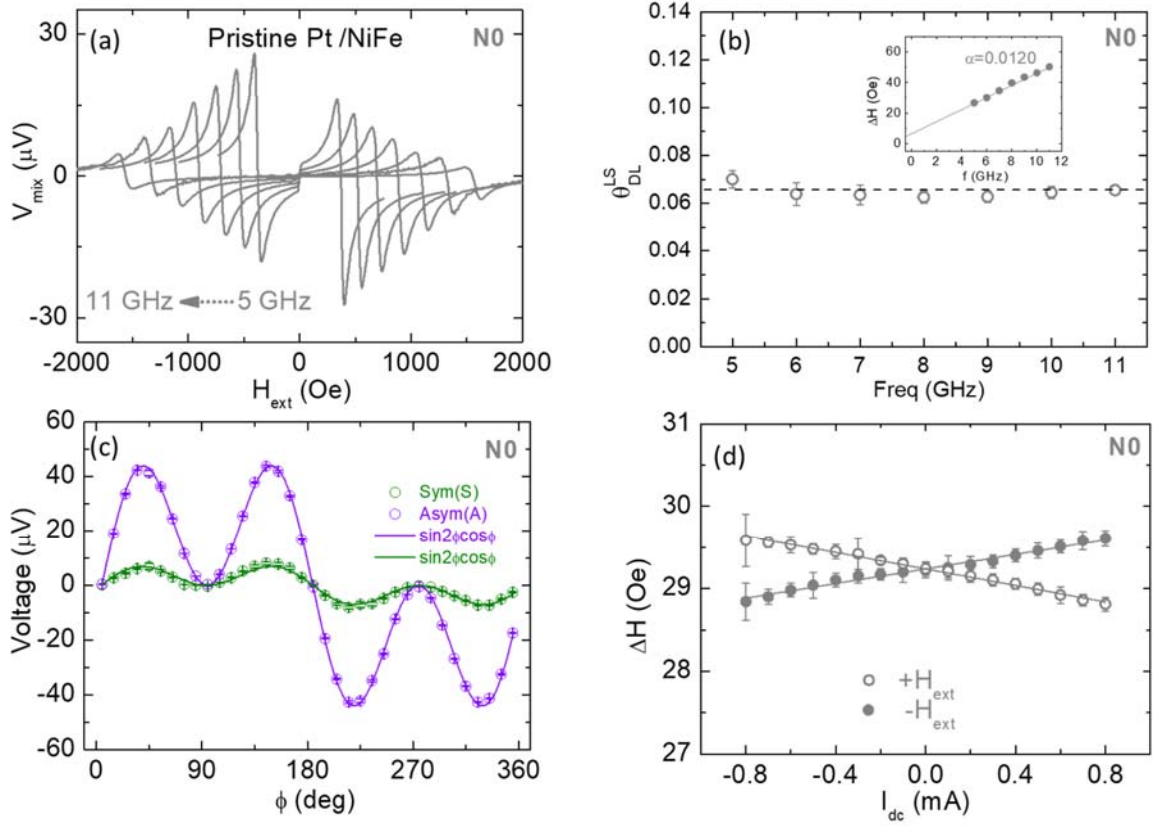


Figure S5: (a) ST-FMR spectra showing  $V_{\text{mix}}$  and (b)  $\theta_{\text{DL}}^{\text{LS}}$  obtained for  $f = 5$  to 11 GHz for sample N0: Pristine Pt/NiFe. Inset shows  $\Delta H$  vs  $f$  (with solid lines as linear fit). (c) Angular dependence of Symmetric and Antisymmetric components. (d) Varying  $\Delta H$  plotted as a function of  $I_{\text{dc}}$  (+/- 0.8 mA) for  $f = 5$  GHz with slope determined from linear fit (solid lines).

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