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Observation of Self-induced Spin-Orbit Torques in Ni-Fe layer with vertical gradient of magnetization

Y. Hibino*, T. Taniguchi, K. Yakushiji, H. Kubota and S. Yuasa

*1 Research Center for Emerging Computational Technologies (RCECT), National Institute of Advanced Industrial Science and Technology
(AIST), Tsukuba, Ibaraki, 305-8568, Japan*

Single ferromagnetic material generates transverse spin currents via in-plane charge current application and can exert spin-orbit torques (SOTs) on its magnetization, namely, self-induced SOTs when the inversion symmetry in the bulk and/or interface is broken. In this Letter, we experimentally demonstrated that introducing a vertical gradient of magnetization within a ferromagnet is an effective way to generate self-induced SOTs. Self-induced SOTs in Ni-Fe alloys with a magnetization gradient are studied using spin-torque ferromagnetic resonance. It was found that the gradient direction of magnetization in Ni-Fe layer can control not only the magnitude of the SOTs but even the sign of the torques. We propose a model to analyze self-induced SOTs under magnetization gradient and reveal that the asymmetric SOT profiles within a ferromagnet due to spatial variation of magnetic moment plays a dominant role in generating efficient self-induced SOTs. Our findings provide a new perspective on understanding the mechanism of generating self-induced SOTs and how to enhance their torque efficiency without the use of heavy metal elements.

*e-mail: y-hibino@aist.go.jp

1 Current-induced spin-orbit torques (SOTs) acting on
2 ferromagnetic materials (FMs) enable ultra-fast and efficient
3 manipulation of magnetization which can be applied to the
4 writing method of magnetic random-access memories [1-4]. The
5 driving source of SOTs is the injection or accumulation of spin
6 angular momentum to the FMs. The spin Hall effect in non-
7 magnetic materials (NMs) and the Rashba-Edelstein effect at the
8 interfaces are typical examples of driving sources, which have
9 been observed in the bilayer structure of FMs and NMs
10 (NM/FM) [5,6].

11 Recently, it has been revealed that the charge-to-spin
12 conversion phenomena, including the spin Hall effect, emerge
13 not only in NMs but also in FMs [7-31]. The charge-to-spin
14 conversion in FMs provides various unique features of SOTs.
15 One is the emergence of unconventional SOTs which have
16 different symmetry from SOTs induced by spin Hall effect in
17 NMs. This originates from the additional charge-to-spin
18 conversion due to the presence of magnetic moment [12-17].
19 Another unique feature is the emergence of self-induced SOTs,
20 that is, the SOTs acting within an FM via the spin current
21 generated within the FM itself. It has been revealed that self-
22 induced SOTs occur in various FMs such as GaMnAs [18], Ni-
23 Fe [19-21], Co-Pt [22-24], Fe-Pt [25-28], Fe-Mn [29], and Co-
24 Tb [30,31]. It has also been demonstrated that self-induced SOTs
25 can induce magnetization dynamics such as magnetization
26 reversal [22-27,31] and oscillation [20]. These results suggest
27 that self-induced SOTs are comparable to conventional SOTs
28 using NM/FM bilayers, thus representing a new technical
29 possibility for controlling magnetization.

30 Previous studies on self-induced SOTs introduced inversion
31 asymmetry in the out-of-plane direction to generate finite self-

32 induced SOTs due to the following reasons. The spin currents
33 generated by the spin Hall effect within the FM accumulate spin
34 angular momentum with the opposite sign at the top and bottom
35 surfaces of the FM, resulting in self-induced SOTs with the
36 opposite sign (Fig. 1a). If the FM satisfies the inversion
37 symmetry, the average spin accumulation becomes zero
38 resulting in all the self-induced SOTs becoming zero as well. If
39 the inversion symmetry is broken in the FM, the average spin
40 accumulation remains finite resulting in finite self-induced SOTs.
41 One of the ways to break the inversion symmetry is by
42 introducing an asymmetric interface structure [19,22,29].
43 Interfacial asymmetry results in an asymmetric profile of spin
44 accumulation, which generates finite self-induced SOTs (Fig.
45 1b). However, because the asymmetry of spin accumulation is
46 effective only near the interface (or surface), this method limits
47 the efficiency of self-induced SOTs. Another way to induce
48 structural asymmetry is to introduce a compositional gradient
49 within the FM layer [23-31]. This method is expected to improve
50 the efficiency of self-induced SOTs compared to the previous
51 method. Several mechanisms of self-induced SOTs obtained via
52 a composition gradient have been discussed so far, e.g., a spatial
53 gradient of spin transport parameters (Fig. 1c), such as the spin
54 Hall angle and resistivity, due to the disorder gradient [23-25,27],
55 spatial gradients in the internal strain [28], and bulk-driven
56 Rashba-Edelstein effects [26,30,31]. However, the detailed
57 mechanisms and how to precisely control these self-induced
58 SOTs have remained elusive.

59 In this letter, we propose an alternative mechanism for the self-
60 induced SOTs driven by composition gradient: the presence of a
61 vertical gradient of the magnetization M_s within a FM. The SOT
62 acting on the magnetic moment in a certain volume is inversely

1 proportional to M_s . Therefore, when the inversion symmetry is
2 broken by the gradient of M_s within the FM, the total self-
3 induced SOTs remain finite in the FM (Fig. 1d). To verify this
4 idea, we quantitatively evaluated the SOT efficiency within the
5 Ni-Fe alloy with a vertical gradient of M_s using spin-torque
6 ferromagnetic resonance (ST-FMR). The gradient of M_s is
7 introduced by forming a Ni composition gradient along the film
8 deposition direction. Despite the use of heavy metal elements
9 (eg: Pt, Tb) within FMs [21-27,29,30], we show that not only the
10 magnitude, but also the sign of the self-induced SOTs can be
11 controlled by the direction of the gradient. We also proposed a
12 model to calculate self-induced SOTs under the vertical gradient
13 of M_s , spin Hall angle, and resistivity, and we found that the
14 spatial variation in M_s plays an important role in generating self-
15 induced SOTs. Model calculations show that the self-induced
16 SOTs of a FM with a M_s gradient can significantly enhance the
17 SOT efficiency compared with those obtained from a uniform
18 FM with interface asymmetry.

19 For this study, we deposited two magnetic stacks with two
20 different types of vertical M_s gradient on a thermally oxidized Si
21 substrate using an ultrahigh-vacuum magnetron sputtering
22 system (Cannon-Anelva C-7100). Stacking structures were as
23 follows (Fig. 2a): Ta-B (t) / Ni-Fe (5) / MgO / TaO_x (thickness in
24 nanometers). The amorphous Ta-B (Ta₈₀B₂₀) layer acts as a
25 buffer layer to improve the flatness of deposited films, and the
26 thickness t was varied from 0 to 3 nm. The Ni-Fe layer consists
27 of five layers with different Ni compositions which are Ni,
28 Ni_{87.5}Fe_{12.5}, Ni_{79.5}Fe_{20.5}, Ni₇₀Fe₃₀, and Ni₄₈Fe₅₂. Note that the
29 magnetic moment in Fe is larger than that of Ni, which results in
30 a M_s gradient with Ni composition [32]. In addition, we found
31 that the resistivity ρ of the Ni-Fe alloy decreases with Ni
32 composition [32]. We prepared two types of vertical gradient
33 structure: One is decreasing the Ni composition from the
34 substrate side (type A) and the other is increasing the Ni
35 composition from the substrate side (type B). As for the
36 reference structure, Ta-B ($t = 1, 2, 3$) / Ni_{79.5}Fe_{20.5} (5) / MgO /
37 TaO_x, with a FM layer of uniform Ni composition, was also
38 prepared. To verify the composition gradients of type A and B
39 systems, we performed scanning electron microscopy (STEM)
40 and energy-dispersive X-ray spectroscopy (EDXS) of type-A
41 and type-B stacks with $t = 3$ nm which are shown in Fig. 2b and
42 2c. The EDXS spectroscopy profiles along the vertical axis in
43 both structures show an inhomogeneous distribution of Fe and
44 Ni in the Ni-Fe layer. The EDXS intensity ratio of Fe to that of
45 Ni (I_{Fe}/I_{Ni}) shows linear decrease (increase) in type A (B)
46 structure which is evidence of the presence of a vertical
47 composition gradient in Ni-Fe layer. The stacks were patterned
48 as micro-strip devices of 100 μm in length and 10 μm in width
49 using conventional photolithography and Ar-ion milling. The
50 electrical contacts were formed by depositing Cr (5 nm) / Au
51 (160 nm) electrodes using the liftoff method.

52 To investigate the SOTs acting on the Ni-Fe layer, we
53 conducted ST-FMR measurements [45–47]. A schematic of the

54 measurement setup is shown in Fig. 3a. We applied radio
55 frequency (rf) current (I_{rf}) with GHz-order frequency to the
56 microstrips and measured the rectified voltage V_{FMR} via the
57 direct current (dc) port of bias-T. The ST-FMR spectra were
58 measured by sweeping a magnetic field H_{ext} under various in-
59 plane angles φ . Fig. 3b and 3c show the ST-FMR spectra of type-
60 A and B structure with $t = 3$ nm, respectively. In both structures,
61 V_{FMR} was well fitted by Lorentzian curve $V_{\text{FMR}} = V_s S(H_{\text{ext}}) +$
62 $V_A A(H_{\text{ext}})$ which consist of symmetric component $S(H_{\text{ext}})$ and
63 anti-symmetric component $A(H_{\text{ext}})$. The Lorentzian fitting
64 curves show that the sign of V_s and V_A is reversed by changing
65 the gradient type. Note that the large difference in magnitude of
66 V_A between type-A and B structures may originate from the
67 offset of Oersted torque from the Ta-B buffer layer. The sign
68 reversal of the V_s and V_A can be explained either by the sign
69 reversal of R_{AMR} or of the SOTs acting on the Ni-Fe layer. We
70 confirmed that $R_{\text{AMR}} > 0$ for both structures from the φ -
71 dependence of the device resistance as shown in the insets of
72 Figs. 3d and 3e. Therefore, the sign reversal and large
73 modulation of the V_s and V_A between the two structures is
74 attributable to the sign reversal of the SOTs. Furthermore, we
75 performed an in-plane angular dependence study of the V_s and
76 V_A in both systems, as shown in Fig. 3d and 3e. The angular
77 dependencies of $V_{s(A)}$ in both systems are well fitted by a
78 $\cos^2 \varphi \sin \varphi$ function, indicating that the SOTs acting on both
79 systems have the same symmetry with the spin Hall effect [47].
80 Note that the spin Hall effect in the Ta-B buffer layer [48] does
81 not result in sign reversal of the SOTs because the buffer layer is
82 fixed to the bottom of the Ni-Fe layer in both structures. As a
83 quantitative study, we estimated the efficiencies of the damping-
84 like component of the SOT (sum of the field-like component of
85 the SOT and the Oersted torque) under unit electric field ξ_{DL}^E
86 ($\xi_{\text{FL+Oe}}^E$) using the φ dependence of $V_s(V_A)$ [46,47]. It should
87 be noted that Oersted torque contribution originates from two
88 factors. One is from the Ta-B buffer layer, and the other is from
89 an inhomogeneous current distribution within the Ni-Fe layer
90 due to the resistivity gradient [32]. We estimated ξ_{DL}^E ($\xi_{\text{FL+Oe}}^E$)
91 in type A and B structures to be 32700 ± 600 (38600 ± 200)
92 $\Omega^{-1}\text{m}^{-1}$ and -46800 ± 700 (-3500 ± 400) $\Omega^{-1}\text{m}^{-1}$, respectively.
93 We note that the efficiencies of the damping-like component of
94 SOT under unit current density (ξ_{DL}^j) in type-A(B) structures is
95 estimated to be 2.2 (-2.5) % which is comparable to that of Co-
96 Pt [22-24] and Co-Tb [31] with a composition gradient, although
97 no heavy metal elements were used in this study. Moreover, ξ_{DL}^j
98 is an order of magnitude larger than that of a uniform Ni-Fe
99 single layer with asymmetric interfaces [21].

100 Let us now discuss the origins of self-induced SOTs in the
101 present system. We consider four contributions. The first one
102 arises from the interfacial asymmetry at the top (Ni-Fe/MgO)
103 and bottom (Ta-B/Ni-Fe) surfaces. This contribution is similar
104 to that discussed in Refs. [19,21]. The second and third possible
105 origins can be attributed to the vertical gradients of spin Hall
106 angle and resistivity due to the compositional gradient [27]. The

last one is the vertical gradient of the magnetization, which is newly proposed in this work. For the first three origins, the spin accumulation μ becomes asymmetric with respect to the FM center due to the different boundary condition or the spatial variations of the transport parameters (spin Hall angle or resistivity). SOTs originate from an exchange interaction between the spin accumulation and local magnetization [49]. Therefore, a local SOT, acting on the magnetic moments in a volume ΔV , is proportional to $\mu \times \mathbf{m}/(M_s \Delta V)$, where $\mathbf{m}$ is the unit vector pointing in the direction of the local magnetic moment. Because of the asymmetric distribution of the spin accumulation, the total SOT, which is an average of the local SOTs over FM layer, remains finite. For the fourth origin, the magnitude of SOTs varies spatially due to the variation in M_s . This is because the magnitude of the SOT is determined by the transferred spin angular momentum per magnetic moment, which is mathematically represented by the factor $1/(M_s \Delta V)$. Therefore, self-induced SOTs via M_s gradient can be generated even if the asymmetric profile of μ is negligible.

To compare these origins, we quantified the self-induced SOTs from drift-diffusion spin transport theory [49] with additional terms originating from the compositional gradient. The calculation details are summarized in the [Supplemental Material](#) [32]. The basic structure consists of a non-magnetic spin-sink layer, the FM layer, and an oxide layer, as schematically shown in Fig. 4(a). To evaluate the contributions of the four origins mentioned above to the self-induced SOTs, we set the values of the parameters in this structure comprehensively, as summarized in Table I. In Case I, the magnetization M_s , spin Hall angle θ_{SHE} , and resistivity ρ are spatially uniform in FM. In the other cases, we introduce the spatial gradient of M_s (Case II), θ_{SHE} (Case III), and ρ (Case IV) in FM. For each case, we consider two directions of the gradient, distinguished by the labels, “A” and “B”. The values of M_s and ρ are estimated from the present experiment [32]. The value of θ_{SHE} is derived from the previous reports for Ni ($\theta_{\text{SHE}} = 0.03$) and Fe ($\theta_{\text{SHE}} = -0.01$) [11]. Figures 4(b)-4(d) show the spatial profile of the spin accumulation in Case II-A, III-A and IV-A. Note that the spin accumulation for Case I and II-B is same with that of Case II-A. Here, $\mu_{y(z)}$ is the spin accumulation is $y(z)$ -axis direction for which the coordination is shown in Fig. 4a. In Case II-A, the profiles of the spin accumulations are approximately symmetric with respect to the center of the FM, even though the interfaces are asymmetric. This result suggests that the contribution of the interfacial asymmetry to the self-induced SOT is small. On the other hand, in cases III-A and IV-A, the profiles of the spin accumulations are asymmetric with respect to the FM center. This is because the spatial variations of the spin Hall angle and the resistivity result in spatially asymmetric generation of spin accumulations.

Next, we evaluated the local SOTs, $\mu \times \mathbf{m}/(M_s \Delta V)$, in the unit of angular frequency and per electric field E with a 0.5 nm step. The results are shown in Fig. 4(e)-4(g) for Case II-A, III-A,

and IV-A. The damping-like and field-like component of the local SOTs correspond to τ_{DL}/E and τ_{FL}/E , respectively. We note that the profile of the local SOT for the Case II-A is significantly asymmetric, even though the spatial profile of the spin accumulations is approximately symmetric. This asymmetric SOT originates from the spatial variation of M_s . The asymmetric profiles of the local SOTs for the Case III-A and IV-A arise from the spatial variation of the spin accumulations. The sums of these local SOTs, $T_{\text{DL(FL)}}/E = \sum \tau_{\text{DL(FL)}}/E$, are summarized in Fig. 4(h), which correspond to the SOT efficiencies measured by the experiments. Comparing these values with the experimental results, we first notice that the interfacial asymmetry in Case I is negligible. On the other hand, large $T_{\text{DL(FL)}}/E$ and its sign reversal with the gradient direction are observed in Case II (M_s gradient) and Case IV (ρ gradient). Note also that the torque efficiencies in these cases agree with the experimental results. The torque efficiencies for Case III-A and III-B show no sign reversal of T_{DL}/E which indicate that the SOT induced by θ_{SHE} gradient is negligibly small compared with the SOT induced by the interfacial asymmetry. The magnitude of the SOT efficiency induced by the θ_{SHE} gradient, which corresponds to the difference of $T_{\text{DL(FL+Oe)}}/E$ between Case III-A and III-B, is approximately one order of magnitude smaller than that of Cases II and IV, as well as the experimental results. Furthermore, comparing Cases II and IV, the torque efficiency in Case II is larger than that in Case IV. We also calculated $T_{\text{DL(FL+Oe)}}/E$ considering both the M_s and θ_{SHE} gradients. However, the calculated results did not change much compared to Case II. Summarizing these results, we conclude that the spatial gradient of M_s is the dominant contribution to the self-induced SOT in the present system. We notice that the self-induced SOT due to the gradient of M_s provides an appropriate sign even when the model is applied to Co-Pt and Fe-Pt systems [23,27] where M_s decreases with increasing Pt composition. In the case of ferrimagnets, such as Co-Tb and Gd-Fe-Co, SOT rapidly increases in the vicinity of compensation point where M_s approaches to ~ 0 . Therefore, self-induced SOT in ferrimagnet is governed by the local SOT acting on the region in the vicinity of the compensation point [50,51] which can also qualitatively explain the sign reversal of self-induced SOT with the gradient direction [31]. Lastly, we note that other parameters, such as the spin diffusion length, may also vary spatially and lead to a self-induced SOT. An investigation of such possibilities will form part of our future work.

We now discuss the other possible effects which may explain the sign reversal of SOTs observed in our experimental results besides that of self-induced SOTs. One is the Rashba-Edelstein effect induced SOTs from the top and bottom interfaces [52,53]. The second is the current induced torque originating from the orbit Hall effect from the Ta-B buffer layer, namely, orbital torques (OTs) [54-57]. To examine these effects, we investigated the Ta-B thickness t in type-A and B structures. Especially in the case of $t = 0$ nm, the top and bottom interface structures were

more symmetrical than when $t \neq 0$. The contribution of OT can also be eliminated in the $t = 0$ structure because there would be no orbital Hall effect from the Ta-B layer. Figures 5a and 5b show the ST-FMR spectra of type-A and B structures with $t = 0$, respectively. A sizable V_s was observed in both structures indicating the existence of a sizable damping-like component of SOT efficiency despite the absence of a non-magnetic buffer layer. Moreover, the sign of V_s is reversed upon gradient direction which indicates that the sign reversal of SOTs acting on Ni-Fe layer does not contribute to either SOTs induced by Rashba-Edelstein effect or OTs, but rather to the self-induced SOT acting within the Ni-Fe layer. Figures 5c and 5d show the Ta-B thickness (t) dependence of ξ_{DL}^E and ξ_{FL+Oe}^E in type-A, type-B, and the reference structures, respectively. The ST-FMR spectra and ϕ dependence of V_s and V_A for each t and structures are summarized in the Supplemental Material [32]. The estimated $|\xi_{DL}^E|$ and $|\xi_{FL+Oe}^E|$ in the reference structure show lower value compared to the type-A and type-B structure which is also consistent with the calculation result of Case I shown in Fig. 4h. We note that a slight sign reversal of ξ_{DL}^E in the reference structure with $t = 1$ nm was observed which we speculate is due to an interfacial contribution [52,53]. To extract the contribution of spin Hall effect induced SOTs from the Ta-B layer, we plotted the differential of ξ_{DL}^E between type-A and type-B structure, shown in red plot. The differential data of ξ_{DL}^E increased rapidly with t and saturated at ~ 2 nm. The differential data of ξ_{FL+Oe}^E show almost constant in $t \neq 0$ nm. The rapid enhancement of differential ξ_{DL}^E with t can be explained by the asymmetric spin accumulation profile within the Ni-Fe layer via insertion of Ta-B buffer layer. Previous studies have reported that torque efficiency of OTs does not saturate in such short thickness region [56-58]. This is because the diffusion length of the orbital angular momentum is much longer than that of the spin angular momentum. Therefore, our results, which show rapid saturation of ξ_{DL}^E , further support that the observed SOT are not attributed to OTs but to self-induced SOTs.

In conclusion, we have experimentally demonstrated that the composition gradient in Ni-Fe alloy significantly modulates the magnitude and sign of the self-induced SOTs. The torque efficiency of the damping-like torque in two different gradient structures measured by the ST-FMR experiments were estimated to be 32700 ± 600 and $-46800 \pm 700 \text{ } \Omega^{-1}\text{m}^{-1}$, depending on the direction of the composition gradient. These values are comparable to previous results from composition gradients using heavy metal elements, even though no heavy metal elements were used. We have also proposed a new origin of these torques, namely, the gradient of the magnetization. Since the SOT strength is the spin angular momentum per magnetic moment and is transferred from the spin accumulation, the spatial variation of the magnetization results in that of the local SOT, and thus, the total SOT remains finite. We have examined the contribution of the spatial variation of the magnetization to the self-induced SOTs by developing a spin transport theory and compared it to other contributions, such as the interfacial asymmetry. Using the experimental values, we have calculated the SOTs for various cases and found that the spatial variation of the magnetization provides the dominant contribution to the SOTs. These findings show quantitative agreement with the experiments and qualitatively explains previous reports. These results show that the magnetization gradient can be an alternative origin to generate a finite self-induced SOT which could be useful for realizing energy-efficient SOT-based devices. The authors thank S. Tamaru, T. Yamamoto, and A. Spiesser for technical supports and valuable discussions. This work is supported by JSPS KAKENHI (no. 23H01477) and partially supported by JST-Mirai Program (no. JPMJMI20A1), and JST-CREST Program (no. JPMJCR18T3). A part of this work was conducted at the AIST Nano-Processing Facility supported by “Nanotechnology Platform Program” of the Ministry of Education, Culture, Sports, Science and Technology (MEXT), Japan.

[1] R Ramaswamy, J. M. Lee, K. Cai, and H. Yang, “Recent advances in spin-orbit torques: Moving towards device applications”, *Appl. Phys. Rev.* **5**, 031107 (2018).
[2] X. Qiu, Z. Shi, W. Fan, S. Zhou, and H. Yang, “Characterization and Manipulation of Spin Orbit Torque in Magnetic Heterostructures”, *Adv. Mater.* **30**, 1705699 (2018).
[3] A. Manchon, J. Železný, I. M. Miron, T. Jungwirth, J. Sinova, A. Thiaville, K. Garello, and P. Gambardella, “Current-induced spin-orbit torques in ferromagnetic and antiferromagnetic systems”, *Rev. Mod. Phys.* **91**, 035004 (2019).
[4] J. Ryu, S. Lee, K.-J. Lee, and B.-G. Park, “Current-Induced Spin-Orbit Torques for Spintronic Applications”, *Adv. Mater.* **32**, 1907148 (2020).
[5] I. M. Miron, K. Garello, G. Gaudin, P. J. Zermatten, M. V. Costache, S. Auffret, S. Bandiera, B. Rodmacq, A. Schuhl, and P. Gambardella, “Perpendicular switching of a single ferromagnetic

layer induced by in-plane current injection”, *Nature* **476**, 189-193 (2011).
[6] L. Liu, C.-F. Pai, Y. Li, H. W. Tseng, D. C. Ralph, and R. A. Buhrman, “Spin-Torque Switching with the Giant Spin Hall Effect of Tantalum”, *Science* **336**, 555-558 (2012).
[7] B. F. Miao, S. Y. Hunag, D. Qu, and C. L. Chien, “Inverse Spin Hall Effect in a Ferromagnetic Metal”, *Phys. Rev. Lett.* **111**, 066602 (2013).
[8] A. Tsukahara, Y. Ando, Y. Kitamura, H. Emoto, E. Shikoh, M. P. Delmo, T. Shinjo, and M. Shiraishi, “Self-induced inverse spin Hall effect in permalloy at room temperature”, *Phys. Rev. B* **89**, 235317 (2014).
[9] C. Du, H. Wang, F. Yang, and P. C. Hammel, “Systematic variation of spin-orbit coupling with d -orbital filling: Large inverse spin Hall effect in 3d transition metals”, *Phys. Rev. B* **90**, 140407(R) (2014).
[10] H. Wang, C. Du, P. C. Hammel, and F. Yang, “Spin Current and

- inverse spin Hall effect in ferromagnetic metals probed by Y3Fe5O12-based spin pumping”, *Appl. Phys. Lett.* **104**, 202405 (2014).
- [11] Y. Omori, E. Sagasta, Y. Niimi, M. Gradhand, L. E. Hueso, F. Casanova, and Y.-C. Otani, “Relation between spin Hall effect and anomalous Hall effect in 3d ferromagnetic metals”, *Phys. Rev. B* **99**, 014403 (2019).
- [12] Y. Hibino, K. Yakushiji, A. Fukushima, H. Kubota, and S. Yuasa, *Phys. Rev. B* **99**, 014403 (2020).
- [13] Y. Hibino, T. Taniguchi, K. Yakushiji, A. Fukushima, H. Kubota, and S. Yuasa, “Giant charge-to-spin conversion in ferromagnet via spin-orbit coupling”, *Nat. Commun.* **12**, 6254 (2021).
- [14] A. M. Humphries, T. Wang, E. R. Edwards, S. R. Allen, J. M. Shaw, H. T. Nembach, J. Q. Xiao, T. J. Silva, and X. Fan, “Observation of spin-orbit effects with spin rotation symmetry”, *Nat. Commun.* **8**, 911 (2017).
- [15] S.-H. C. Baek, V. P. Amin, Y.-W. Oh, G. Go, S.-J. Lee, G.-H. Lee, K.-J. Kim, M. D. Stiles, B.-G. Park, and K.-J. Lee, “Spin currents and spin-orbit torques in ferromagnetic trilayers”, *Nat. Mater.* **17**, 509-513 (2018).
- [16] S. Iihama, T. Taniguchi, K. Yakushiji, A. Fukushima, Y. Shiota, S. Tsunegi, R. Hiramatsu, S. Yuasa, Y. Suzuki, and H. Kubota, “Spin-transfer torque induced by the spin anomalous Hall effect”, *Nat. Electron.* **1**, 120-123 (2018).
- [17] C. Safranski, E. A. Montoya, and I. N. Krivorotov, “Spin-orbit torque driven by a planar Hall current”, *Nat. Nanotechnol.* **14**, 27-30 (2019).
- [18] A. Chernyshov, M. Overby, X. Liu, J. K. Furdyna, Y. Lyanda-Geller, and L. P. Rokhinson, “Evidence for reversible control of magnetization in a ferromagnetic material by means of spin-orbit magnetic field”, *Nat. Phys.* **5**, 656-659 (2009).
- [19] W. Wang, T. Wang, V. P. Amin, Y. Wang, A. Radhakrishnan, A. Davidson, S. R. Allen, T. J. Silva, H. Ohldag, D. Balzar, B. L. Zink, P. M. Haney, J. Q. Xiao, D. G. Cahill, V. O. Lorenz, and X. Fan, “Anomalous spin-orbit torques in magnetic single-layer films”, *Nat. Nanotechnol.* **14**, 819-824 (2019).
- [20] M. Haider, A. A. Awad, M. Dvornik, R. Khymyn, A. Houshang, and J. Åkerman, “A single layer spin-orbit torque nano-oscillator”, *Nat. Commun.* **10**, 2362 (2019).
- [21] T. Seki, Y. C. Lau, S. Iihama, and K. Takanashi, “Spin-orbit torque in a Ni-Fe single layer”, *Phys. Rev. B* **104**, 094430 (2021).
- [22] L. Zhu, X. S. Zhang, D. A. Muller, D. C. Ralph, and R. A. Buhrman, “Observation of Strong Bulk Damping-Like Spin-Orbit Torque in Chemically Disordered Ferromagnetic Single Layers”, *Adv. Funct. Mater.* **30**, 2005201 (2020).
- [23] X. Xie, X. Zhao, Y. Dong, X. Qu, K. Aheng, X. Han, X. Han, Y. Fan, L. Bai, Y. Chen, Y. Dai, Y. Tian, and S. Yan, “Controllable field-free switching of perpendicular magnetization through bulk spin-orbit torque in symmetry-broken ferromagnetic films”, *Nat. Commun.* **12**, 2473 (2021).
- [24] Z. Chen, L. Liu, Z. Ye, Z. Chen, H. Zheng, W. Jia, Q. Zeng, N. Wang, B. Xiang, T. Lin, J. Liu, M. Qiu, S. Li, J. Shi, P. Han, and H. An, “Current-induced magnetization switching in a chemically disordered Al CoPt single layer”, *Appl. Phys. Express* **14**, 033002 (2021).
- [25] S. Q. Zheng, K. K. Meng, Q. B. Liu, J. K. Chen, J. Miao, X. G. Xu, and Y. Jiang, “Disorder dependent spin-orbit torques in L1 FePt single layer”, *Appl. Phys. Lett.* **117**, 242403 (2020).
- [26] L. Liu, J. Yu, W. Gonzalez-Hernandez, C. Li, J. Deng, W. Lin, C. Zhou, T. Zhou, J. Zhou, H. Wang, Y. Yoong, G. M. Chow, X. Han, B. Dupe, J. Zelenzny, J. Sinova, and J. Chen, “Electrical switching of perpendicular magnetization in a single ferromagnetic layer”, *Phys. Rev. B* **101**, 200402R (2020).
- [27] M. Tang, K. Shen, S. Zu, H. Yang, S. Hu, W. Lu, C. Li, M. Li, Z. Yuan, S. J. Pennycook, K. Xia, A. Manchon, S. Zhou, and X. Qiu, “Bulk Spin Torque-Driven Perpendicular Magnetization Switching in L10 FePt Single Layer”, *Adv. Mater.* **32**, 2002607 (2020).
- [28] L. Zhu, D. C. Ralph, and R. A. Buhrman, “Unveiling the Mechanism of Bulk Spin-Orbit Torques within Chemically Disordered Fe_xPt_{1-x} Single Layers”, *Adv. Funct. Mater.* **31**, 2103898 (2021).
- [29] Z. Luo, Q. Zhang, Y. Zu, Y. Yang, X. Zhang, and Y. Wu, “Spin-Orbit Torque in a Single Ferromagnetic Layer Induced by Surface Spin Rotation”, *Phys. Rev. Appl.* **11**, 064021 (2019).
- [30] J. W. Lee, J. Y. Park, J. M. Yuk, and B. G. Park, “Spin-Orbit Torque in a Perpendicularly Magnetized Ferrimagnetic Tb-Co Single Layer”, *Phys. Rev. Appl.* **13**, 044030 (2020).
- [31] Z. Zhang, Y. Zhang, V. Lopez-Dominguez, L. Sanchez-Tejerina, J. Shi, X. Feng, L. Chen, Z. Wang, Z. Zhang, K. Zhang, B. Hong, Y. Xu, Y. Zhang, M. Carpentieri, A. Fert, G. Finocchio, W. Zhao, and P. K. Amiri, “Field-free spin-orbit torque-induced switching of perpendicular magnetization in a ferrimagnetic layer with a vertical composition gradient”, *Nat. Commun.* **12**, 4555 (2021).
- [32] See Supplemental Material for more details on Ni composition dependence of M_s and ρ , estimation of $\xi_{DL(FL+Oe)}^E$ and $T_{DL(FL)}/E$ from ST-FMR measurement, ferromagnetic resonance properties, estimation of rf current, model calculation of self-induced SOT, and angular dependence of V_s and V_A in various buffer layer thickness and structure type. The Supplemental Material also contains Refs. [33-44].
- [33] T. Gao, A. Qaiumzadeh, H. An, A. Musha, Y. Kageyama, J. Shi, and K. Ando, “Intrinsic Spin-Orbit Torque Arising from the Berry Curvature in a Metallic-Magnet/Cu-Oxide Interface”, *Phys. Rev. Lett.* **121**, 017202 (2018).
- [34] T. Taniguchi, J. Grollier, and M. D. Stiles, “Spin-Transfer Torques Generated by the Anomalous Hall Effect and Anisotropic Magnetoresistance”, *Phys. Rev. Appl.* **3**, 044001 (2015).
- [35] V. P. Amin, and M. D. Stiles, “Spin transport at interfaces with spin-orbit coupling: Formalism”, *Phys. Rev. B* **94**, 104419 (2016).
- [36] V. P. Amin, and M. D. Stiles, “Spin transport at interfaces with spin-orbit coupling: Phenomenology”, *Phys. Rev. B* **94**, 104420 (2016).
- [37] V. P. Amin, J. Zeeman, and M. D. Stiles, “Interface-generated spin currents”, *Phys. Rev. Lett.* **121**, 136805 (2018).
- [38] V. P. Amin, J. Li, M. D. Stiles, and P. M. Haney, “Intrinsic spin currents in ferromagnets”, *Phys. Rev. B* **99**, 220405 (2019).

- [39] K.-W. Kim and K.-J. Lee, “Generalized Spin Drift-Diffusion Formalism in the Presence of Spin-Orbit Interaction of Ferromagnets”, *Phys. Rev. Lett.* **125**, 207205 (2020).
- [40] T. Taniguchi and H. Imamura, “Spin pumping in ferromagnetic multilayers”, *Mod. Phys. Lett. B* **22**, 2909 (2008).
- [41] L. Liu, O. J. Lee, T. J. Gudmundsen, D. C. Ralph, and R. A. Buhrman, “Current-Induced Switching of Perpendicularly Magnetized Magnetic Layers Using Spin Torque from the Spin Hall Effect”, *Phys. Rev. Lett.* **109**, 096602 (2012).
- [42] S. Maekawa, S. O. Valenzuela, E. Saitoh, and T. Kimura, *Spin Current* (Oxford University Press, Oxford, 2012).
- [43] A. Brataas, Y. V. Nazarov, and G. E. W. Bauer, “Spin-transport in multi-terminal normal metal-ferromagnet systems with non-collinear magnetizations”, *Eur. Phys. J. B* **22**, 99 (2001).
- [44] T. Taniguchi, S. Yakata, H. Imamura, and Y. Ando, “Determination of Penetration Depth of Transverse Spin Current in Ferromagnetic Metals by Spin Pumping”, *Appl. Phys. Express* **1**, 031302 (2008).
- [45] L. Liu, T. Moriyama, D. C. Ralph, and R. A. Buhrman, “Spin-Torque Ferromagnetic Resonance Induced by the Spin Hall Effect”, *Phys. Rev. Lett.* **106**, 036601 (2011).
- [46] D. Fang, H. Kurebayashi, J. Wunderlich, K. Vyborny, L. Zarbo, R. P. Campion, A. Casiraghi, B. L. Gallagher, T. Jungwirth, and A. J. Ferguson, “Spin-orbit-driven ferromagnetic resonance”, *Nat. Nanotechnol.* **6**, 413-417 (2011).
- [47] D. MacNeill, G. M. Stiehl, M. H. D. Guimaraes, R. A. Buhrman, J. Park, and D. C. Ralph, “Control of spin-orbit torques through crystal symmetry in WTe₂/ferromagnet bilayers”, *Nat. Phys.* **13**, 300-305 (2017).
- [48] Y. Kato, Y. Saito, H. Yoda, T. Onokuchi, S. Shirotori, N. Shimomura, S. Oikawa, A. Tiwari, M. Ishikawa, M. Shimizu, B. Altansargai, H. Sugiyama, K.Koi, Y. Ohsawa, and A. Kurobe, “Improvement of Write Efficiency in Voltage-Controlled Spintronic Memory by development of a Ta-B Spin Hall Electrode”, *Phys. Rev. Appl.* **10**, 044011 (2018).
- [49] S. Zhang, P. M. Levy, and A. Fert, “Mechanisms of Spin-Polarized Current-Driven Magnetization Switching”, *Phys. Rev. Lett.* **88**, 236601 (2002).
- [50] J. Finely and L. Q. Liu, “Spin-Orbit-Torque Efficiency in Compensated Ferrimagnetic Cobalt-Terbium Alloys”, *Phys. Rev. Appl.* **6**, 054001 (2016).
- [51] W. S. Ham, S. H. Kim, D. H. Kim, K. J. Kim, T. Okuno, H. Yoshikawa, A. Tsukamoto, T. Moriyama, and T. Ono, “Temperature dependence of spin-orbit effective fields in Pt/GdFeCo bilayers”, *Appl. Phys. Lett.* **110**, 242405 (2017).
- [52] G. Allen, S. Manipatruni, D. E. Nikonov, M. Doczy, and I. A. Young, “Experimental demonstration of the coexistence of spin Hall and Rashba effects in β -tantalum/ferromagnet bilayers”, *Phys. Rev. B* **91**, 144412 (2015).
- [53] S. Emori, T. Nan, A. M. Belkessam, X. Wang, A. D. Matyushov, C. J. Babroski, Y. Gao, H. Lin, and N. X. Sun, “Interfacial spin-orbit torque without spin-orbit coupling”, *Phys. Rev. B* **93**, 180402(R) (2016).
- [54] D. Lee, D. Go, H.-J. Park, W. Jeong, W.-W. Ko, D. Yun, D. Jo, G. Go, J. H. Oh, K.-J. Kim, B.-G. Park, B.-C. Min, H. C. Koo, H.-W. Lee, O. Lee, and K.-J. Lee, “Orbital torque in magnetic bilayers”, *Nat. Commun.* **12**, 6710 (2021).
- [55] G. Sala and P. Gambardella, “Giant orbital Hall effect and orbital-to-spin conversion in 3d, 5d, and 4f metallic heterostructures”, *Phys. Rev. Research* **4**, 033037 (2022).
- [56] H. Hayashi, D. Jo, D. Go, T. Gao, S. Haku, Y. Mokrousov, H. W. Lee, and K. Ando, “Observation of long-range orbital transport and giant orbital torque”, *Commun. Phys.* **6**, 32 (2023).
- [57] R. Fukunaga, S. Haku, H. Hayashi, and K. Ando, “Orbital torque originating from orbital Hall effect in Zr”, *Phys. Rev. Research* **5**, 023054 (2023).
- [58] Y.-G. Choi, D. Jo, K.-H. Ko, D. Go, K.-H. Kim, H. G. Park, C. Kim, B.-C. Min, G.-M. Choi, and H.-W. Lee, “Observation of the orbital Hall effect in a light metal Ti”, *Nature* **19**, 52-56 (2023).

Case	M_s (emu/cm ³)	θ_{SHE} (a.u.)	ρ ($\mu\Omega\text{cm}$)
I	750	0.022	50
II-A	300 (z=0nm), 1200 (z=5nm)	0.022	50
II-B	1200 (z=0nm), 300 (z=5nm)	0.022	50
III-A	750	0.03 (z=0nm), 0.01 (z=5nm)	50
III-B	750	0.01 (z=0nm), 0.03 (z=5nm)	50
IV-A	750	0.022	30 (z=0nm), 70 (z=5nm)
IV-B	750	0.022	70 (z=0nm), 30 (z=5nm)

TABLE I: A summary of M_s , θ_{SHE} , and ρ of the various cases used in model calculation. Case I, II, III, and IV corresponds to FM layer with uniform parameter, FM layer introducing spatial gradient of M_s , FM layer introducing spatial gradient of θ_{SHE} , and FM layer introducing spatial gradient of ρ respectively. -A and -B corresponds to the gradient direction which matches the type-A and type-B structure used in ST-FMR measurements.

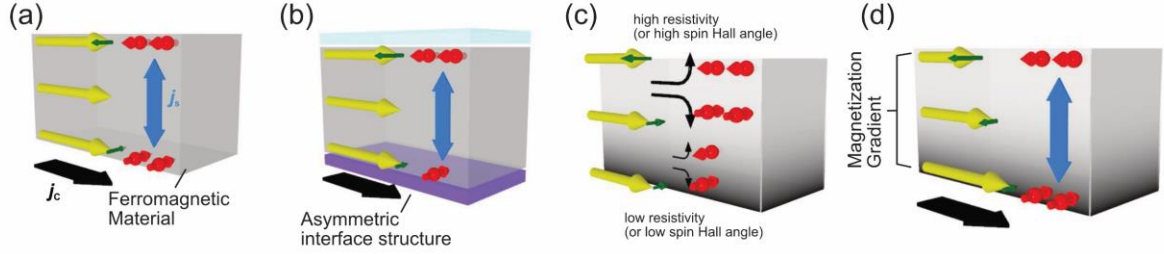


Fig. 1: Schematic of self-induced SOTs in ferromagnetic material (FM) with (a) inversion symmetry, (b) inversion asymmetry due to interface structure, (c) inversion asymmetry with gradient of spin Hall angle (or resistivity), and (d) inversion asymmetry with magnetization gradient. In-plane charge current j_c generates spin current j_s (blue or black arrows) along out-of-plane direction resulting in accumulation of spin moment (red arrows). Spin transfer between local magnetic moment (yellow) and spin accumulation result in generation of self-induced SOTs (green arrows). Magnitude of local magnetic moment and self-induced SOTs are shown as varying lengths of arrows.

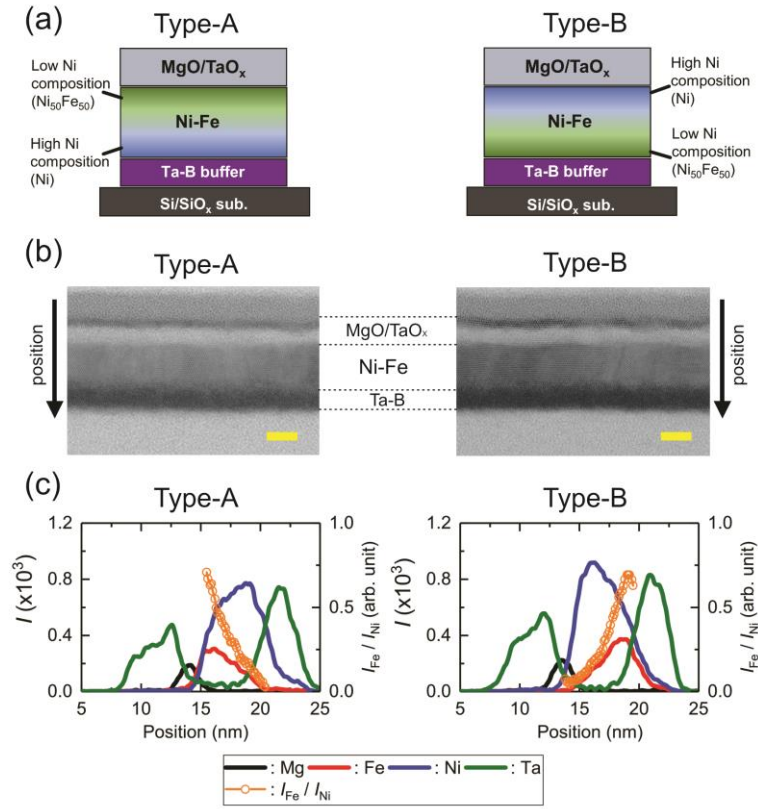


Fig. 2: (a) Schematic of magnetic stacks. Ni composition in Ni-Fe layer in type A(B) stack decrease (increase) composition gradient from the substrate side to the MgO interface. (b) STEM image of two sample. The yellow bar shows the scale bar of 2.5 nm. (c) EDXS vertical profile of Mg, Fe, Ni, and Ta in type A (left) and B (right) stack. Right axis represents the EDXS intensity ratio of Fe to that of Ni (I_{Fe}/I_{Ni}).

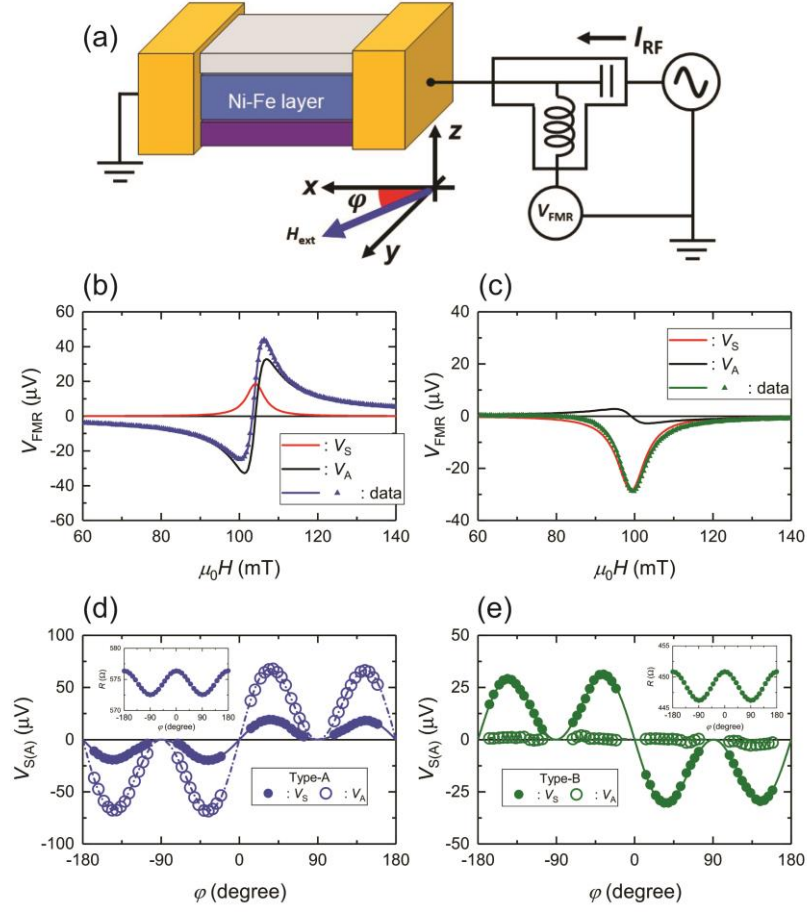


Fig. 3: (a) Schematic of measurement setup for ST-FMR. (b and c) ST-FMR spectra for (b) type A and (c) type B stacks with $t = 3$ nm. In-plane angle (ϕ) and applied microwave frequency (f) is set to 45 degrees and 10 GHz respectively. Red and black solid curves show V_S and V_A component of Lorentzian fitting respectively. (d and e) ϕ -dependence of V_S (solid symbol) and V_A (open symbol) for (d) type-A and (e) type-B sample with $t = 3$ nm. Solid and dotted curves denote fitting results. Inset of (d) and (e) show the ϕ -dependence of device resistance R for each structure.

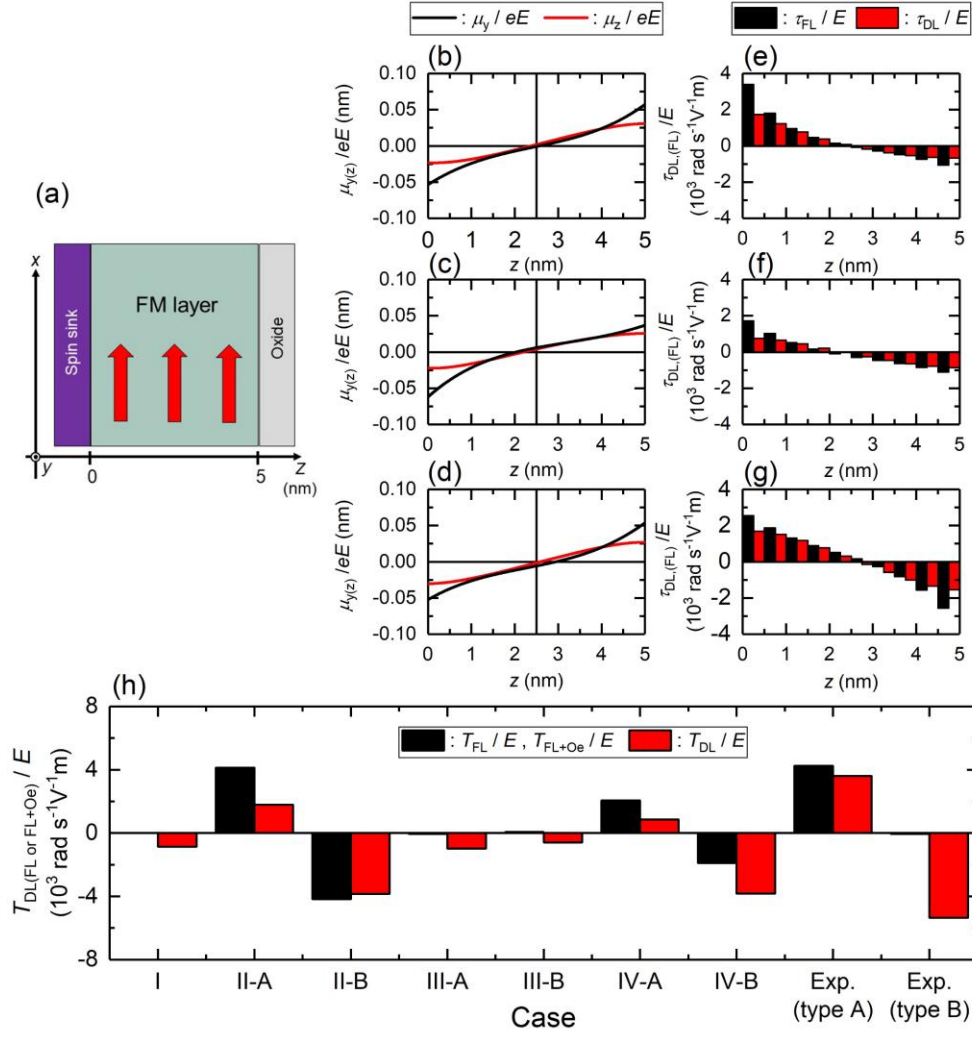


Fig. 4: (a) Schematic of proposed model system consisting of non-magnetic spin-sink layer / FM / oxide layer. Red arrow shows the magnetization pointing along +x direction in the calculation. Charge current flow direction is set to +x direction. (b)-(d) Spin accumulation ($\mu_{y(z)}/eE$) profile in FM layer for (b) Case II-A, (c) Case III-A, and (d) Case IV-A. (e)-(g) Calculated t_{DL}/E and t_{FL}/E profile in FM layer for (e) Case II-A, (f) case III-A, and (g) case IV-A. (g) torque efficiency of self-induced SOTs (T_{DL}/E and $T_{FL(FL+Oe)}/E$) for each calculation cases and estimated experimental value for $t = 3$ nm devices shown in Fig. 3. Black and red represents the field-like and damping-like components of self-induced SOTs ($T_{FL(FL+Oe)}/E$ and T_{DL}/E respectively).

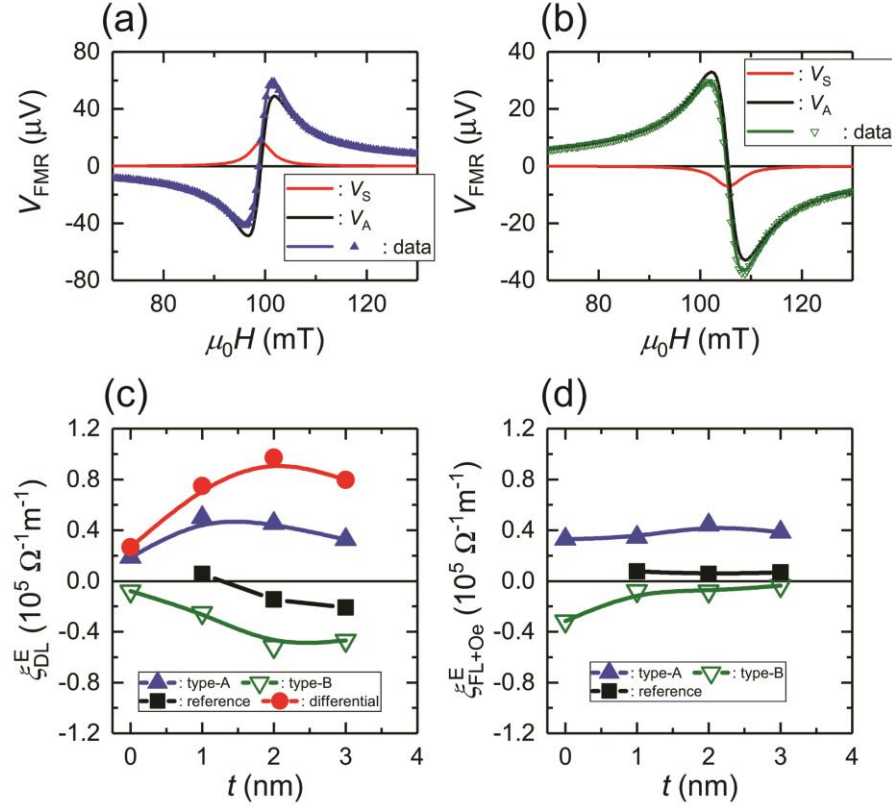


Fig. 5: ST-FMR spectra for (a) type A and (b) type B sample with no Ta-B buffer layer. Measurement parameters are same as in Figs. 2b and 2c. (c) and (d) Ta-B buffer layer thickness dependence of (c) ξ_{DL}^E and (d) ξ_{FL+Oe}^E for type A (blue solid symbol), type B (green open symbol), and differential ξ_{DL}^E between type A and B (red circle symbol). The Solid curves are guides for eyes. Black square symbol show ξ_{DL}^E and ξ_{FL+Oe}^E for reference structure with uniform Ni composition.