Enhancing Spin-Orbit Torque by Strong Interfacial Scattering From Ultrathin Insertion Layers

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Enhancing spin-orbit torque by strong interfacial scattering from ultra-thin insertion layers

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Increasing dampinglike spin-orbit torque (SOT) is both of fundamental importance for enabling new research into spintronics phenomena and also technologically urgent for advancing low-power spin-torque memory, logic, and oscillator devices. Here, we demonstrate that enhancing interfacial scattering by inserting ultra-thin layers within a spin Hall metals with intrinsic or side-jump mechanisms can significantly enhance the spin Hall ratio. The dampinglike SOT was enhanced by a factor of 2 via sub-monolayer Hf insertion, as evidenced by both harmonic response measurements and current-induced switching of in-plane magnetized magnetic memory devices with the record low critical switching current of ~73 μA (switching current density ≈ 3.6 × 10^6 A/cm^2). This work demonstrates a very effective strategy for maximizing dampinglike SOT for low-power spin-torque devices.

Keyword: Spin Hall effect, Spin orbit torque, interfacial scattering, MRAM, Magnetic tunnel junction

1. Introduction

Spin-orbit torques (SOTs) generated by the spin Hall effect (SHE) can efficiently switch thin-film nanomagnet devices [1-4], excite magnetization oscillations [5], and drive skyrmion and chiral domain wall displacement [7,8]. Increasing SOT efficiencies is of great importance for enabling new research into spintronics phenomena [1-9] and for advancing technological applications of SOTs [10-13]. Of particular interest in this effort is to develop heavy metals (HMs) that can simultaneously provide a large damping-like SOT efficiency per current density (ξDL), easy growth, good chemical/thermal stability, and the capability to be readily integrated into complex experimental configurations and/or into manufacturing processes. A good representative of such HMs is Pt, which has giant spin Hall conductivity (σSH) arising from the Berry curvature of its band structure [14,15]. For the SHE, ξDL ≡ (2e/ℏ)TmσSHρxx with e, ℏ, ρxx, and Tm being the elementary charge, the reduced Planck constant, and the HM resistivity, the spin transparency of the HM/FM interface [9], ξDL for Pt/ferromagnet (FM) systems is ~0.08 where ρxx ≈ 20 μΩ cm [16]. Recently, impurity scattering has been demonstrated to increase ξDL via enhancing ρxx [17-20]. However, in all the previous work the increase of ξDL was limited (e.g., to ξDL = 0.12-0.3 for 4 nm Pt alloys) due to a fast decrease in σSH with doping level [19] or/and only a weak enhancement of ρxx [17,18]. Exploring new enhancement strategies that can better optimize the trade-offs between ρxx and TmσSH is of both fundamental interest and technological urgency (e.g., for low-power magnetic memories, logic, and oscillators).

In this work, we report that introducing strong interfacial electron scattering via the insertion of sub-monolayers of Hf into Pt can enhance ρxx of a ~4 nm Pt layer by a factor of 5, which beneficially results in 100% enhancement of ξDL (up to 0.37). The increase in ξDL by the ultrathin insertion layers is approximately twice as effective as a uniform alloying of Hf into Pt. This giant enhancement of ξDL by Hf insertion layers is reaffirmed by the deterministic switching of in-plane magnetic tunnel junctions (MTJs) at a low zero-temperature critical current of ≈ 73 μA (current density ≈ 3.6 × 10^6 A/cm^2) as determined from ramp rate measurements.

2. Results and discussions

2.1 Enhancing resistivity by interfacial scattering

The main idea of this work is schematically shown in Fig. 1. In a single metallic layer of Pt, that is not too thin, e.g., 4 nm as typically used for spin-torque magnetic random access memories (MRAMs)[10], the resistivity arises mainly from the electron scattering by impurities and thermal phonons inside the Pt layer and is hence relatively low, e.g., 20-50 μΩ cm at room temperature [16-21]. In contrast, if we “dice” the same Pt layer into several layers by inserting multiple ultra-thin Hf layers during the deposition process, the new Pt/Hf interfaces should introduce strong additional interfacial scattering of electrons and hence greatly enhance the averaged ρxx. The Pt crystal structure between the interfaces can be disrupted less than would be the case for uniform alloying with Hf [19], thereby better preserving the large intrinsic σSH of Pt and better enhancing ξDL.

We sputter-deposited magnetic stacks of Ta 1.0/[Pt d/Hf 0.2]n/Pt d/Co t/MgO 2.0/Ta 1.5 (numbers are layer thicknesses in nm) with d = 0.4, 0.5, 0.6, 0.75, 1, 1.5, 2, and 4 nm, respectively. Here n (≤ 7) is chosen to be the integer that can make the total Pt thickness closest to 4 nm under the constraint that the total Hf thickness is no more than 1.4 nm (note that the spin diffusion length λs of the amorphous Hf is ~1 nm [22]). For the perpendicular magnetic anisotropy (PMA) samples, the Co thickness t is 0.83 nm for d ≥ 1 nm and 0.63 nm for d ≤ 0.75 nm; for in-plane magnetic anisotropy (IMA) samples, t is 1.3 nm for d ≥ 1 nm and 0.93 nm for d ≤ 0.75 nm. The samples were further patterned into 5×60 μm² Hall bars (see Fig. 2(a)) for resistivity and SOT measurements (see Supplemental materials [23]).
measurements (Supporting Information, Figs. S1-S3).

microscopy (STEM)/electron dispersive spectroscopy (EDS)

diffraction/reflectivity or scanning tunneling electron

are too thin to be distinguishable by either x-ray

enhancement despite the fact that the 0.2 nm Hf insertions

cm for Pt 0.85Hf0.15)[18-21], this is a remarkable resistivity

both PMA (blue dots) and IMA (black circles)

eye. The red star denotes the value of

spatially uniform Pt0.87Hf0.13 alloy [19].

As shown in Fig. 2(b), the average resistivity of the [Pt

d/Hf 0.2]d/Pt d multilayer is increased from 37 μΩ cm for d

= 4 nm (pure Pt) to 191 μΩ cm for d =0.4 ([Pt 0.4/Hf

0.2]d/Pt 0.4). Compared to that achieved by alloying or

impurity doping (~83 μΩ cm for Au0.23Pt0.75 and ~110 μΩ

cm for Pt0.85Hf0.15)[18-21], this is a remarkable resistivity

enhancement despite the fact that the 0.2 nm Hf insertions

are too thin to be distinguishable by either x-ray
diffraction/reflectivity or scanning tunneling electron

microscopy (STEM)/electron dispersive spectroscopy (EDS)

measurements (Supporting Information, Figs. S1-S3).

2.2 Magnifying spin torque by interfacial scattering

Figure 2(c) summarizes the values of $\xi_{DL}$ determined

from harmonic response measurements [24,25] on both the

PMA and IMA multilayers as a function of d, with good

agreement between the two types of measurements

(Supporting Information, Figs. S4 and S5). For both the

PMA and IMA samples, $\xi_{DL}$ increases quickly from

~0.17±0.01 at d = 4 nm (pure Pt) to a peak at d = 0.6 nm

and then drops slightly as d increases further to 0.4 nm.
The peak value of $\xi_{DL}$ = 0.37±0.01 for d = 0.6 nm (i.e., [Pt

0.6/Hf 0.2]d/Pt 0.6 multilayers) is significantly higher than

the values reported for Pt0.83Hf0.15 ( $\xi_{DL}$ = 0.15)[19],

Au0.23Pt0.75 ($\xi_{DL}$ ≈ 0.30)[18], β-W ($\xi_{DL}$ = 0.2-0.3)[13,26]

and β-Ta ($\xi_{DL}$ ≈ 0.12)[3]. We attribute the increase of $\xi_{SH}$

for Pt/Hf multilayers to the enhanced resistivity from interface

scattering (see Fig. 2(b)). Based on the comparisons in Fig.

S8 and Table S2, the giant $\xi_{DL}$ for Pt/Hf multilayers can

provide very compelling current and energy efficiencies for

spin torque applications, for instance for SOT-MRAMs, with

a current efficiency superior to any other known material

for practical applications.

The interesting peak behavior of $\xi_{DL}$ at d ≈ 0.6 nm can

be explained as due to a competition between $\rho_{xx}$ that

increases quickly as a function of decreasing d (Fig. 2(b))

and the apparent spin Hall conductivity, $\sigma_{SH} = T_{int}$$\sigma_{SH}$ =

(ℏ/2e) $\xi_{DL}$/$\rho_{xx}$, that decreases sharply as d decreases from 4

nm to 0.4 nm (Fig. 2(d)). This decrease in $\sigma_{SH}$ should be

attributed partly to the enhanced attenuation of spin current

in the Hf insertion layers. The amorphous Hf has a short

$\lambda_s$ of ~1 nm and doesn’t contribute to the generation of the spin

current due to its negligible SHE [22]. Therefore, in the

multilayers with small d where the total Hf thickness

reaches > 1 nm, there should be a strong attenuation of the spin
currents that diffuse to the FM interface from the

bottom Pt layers to exert a SOT. In addition, the decrease of

$\sigma_{SH}$ with d could result in part from a strain-induced
degradation of the Pt band structure (from a well ordered fcc

texture to a nearly amorphous structure, see Fig. S1).

Nevertheless, in the Pt/Hf multilayers $\sigma_{SH}$ is better

preserved compared to that of uniformly doped Pt with Hf

impurities. As shown in Fig. 2(d), $\sigma_{SH}$ for the 4 nm

Pt0.83Hf0.17 is 1.5×10^5 (ℏ/2e)Ω⁻¹m² [19], which is a factor of

2 smaller than that of the Pt/Hf multilayers with similar Hf

“concentration” (i.e. close to [Pt 1/Hf 0.2] 3/Pt 1). This

suggests that such HM multilayers with strong interfacial

scattering can be generally advantageous over the

corresponding impurity doping because in the latter $\sigma_{SH}$
can be degraded more substantially by a stronger disturbance to

the Pt band structure. We speculate that an enhancement of

$\xi_{DL}$ beyond the value of 0.37 that we obtain here should

be possible if the increase of resistivity, the insertion layer

attenuation of spin current, and the insertion-induced Pt

strain can be better balanced, for instance, by using an

insertion material that has a longer $\lambda_s$, and an atomic radius

closer to that of Pt (e.g., Ti) to minimize the disruption of the

Pt crystal lattice and band structure.

2.3 Spin-torque switching of magnetization

Now we show that our optimal Pt/Hf multilayer with

strong interfacial scattering, [Pt 0.6/Hf 0.2]d/Pt 0.6, is a

particularly compelling spin Hall material for SOT research

and technological applications. As the first example, we

show the switching of a PMA Co layer (j_ε = 1.7 ×10^7 A/cm²,

coefficency $H_c$ of 0.43 kOe) enabled by the giant $\xi_{DL}$ due to
the SHE of the [Pt 0.6/Hf 0.2]₆/Pt 0.6 multilayer (Fig. S4). As an independent check of the effectiveness of the enhancement of $\xi_{DL}$ by Pt/Hf interfaces, we demonstrate antidamping switching of in-plane magnetized SOT-MRAM devices with FeCoB-MgO MTJs. We fabricated two types of MRAM devices, Devices A and B. Each MRAM device consists of a 300 nm-wide spin Hall channel of [Pt 0.6/Hf 0.2]₆/Pt 0.6 ($n = 5$ for Device A and 6 for Device B), an elliptical MTJ pillar of Fe₉₀Co₁₅₂₀₇₄₁₆/MgO 1.6/Fe₉₀Co₁₅₂₀₇₄₁₆ 4 (190×45 nm² for Device A or 190×74 nm² for Device B), and protective capping layers of Pt 3/Ru 4 (see the schematic in Fig. 3(a) and the cross-sectional STEM and EDS imaging results in Fig. S3). All devices were annealed at 240 °C. For Device B, a 0.25 nm and a 0.1 nm Hf spacers were inserted at the bottom and top of the 1.6 nm FeCoB free layer, respectively, to suppress the magnetic damping constant ($\alpha$)[27] and reduce the effective magnetization ($4\pi M_{eff}$), thereby reducing the critical current for anti-damping switching [11]. The long axis of the elliptical MTJ pillars was along $y$ direction, transverse to the spin Hall channel and the write-current flow ($x$ direction). In Figs. 3(b)-3(f), we compare the magnetization switching behaviors, $\alpha$, and $4\pi M_{eff}$ of two representative MRAM devices without (Device A, red) and with (Device B, black) the two Hf spacers. Figure 3(b) shows the sharp switching minor loops of the MTJs under an in-plane magnetic field along the long axis of the MTJ pillar ($H_y$). The minor loops are artificially centered after subtraction of the dipole fields ($H_{offset} \approx 150$ Oe for Device A and 180 Oe for Device B) of the 4 nm Fe₉₀Co₁₅₂₀₇₄₁₆ reference layers. $H_y$ of the free layer is 36 Oe for Device A and 9 Oe for device B. The apparent magnetic resonance field $H_{res} = 1.0±0.1)$, as determined by subtraction of the dipole fields ($H_{offset}$ and $H_y$), is not very high, which is attributed to a large background resistance caused during the device fabrication process (i.e., the oxidation of the Ti adhesion layer between the MTJ pillars and the top Pt contact as indicated in Fig. S3).

Figure 3(c) shows the characteristic switching behavior of Devices A and B as the write current in the spin Hall channel is ramped quasi-statically (an in-plane field equal to $H_{offset}$ was applied along pillar long axis to compensate the dipole field from the reference layer). The MTJs show abrupt switching at write currents of 16 $\mu$A for Device A and 20 $\mu$A for Device B. Since thermal fluctuations assist the reversal of a nanoscale MTJ device during slow current ramps, we carried out ramp rate measurements (Fig. 3(d)). Within the macrospin model, the switching current $I_c$ should scale with the ramp rate ($\ell$) following [28]

$$I_c = I_{c0} \left(1 + \frac{1}{\Delta} \ln \frac{\gamma I_{c0}}{\Delta} \right)$$

(1)

Here $I_{c0}$ is the critical switching current in absence of thermal fluctuations, $\ell$ the stability factor that represents the normalized magnetic energy barrier for reversal between the P and AP states, and $\gamma$ the thermal attempt time which we assume to be 1 ns. By fitting to Eq. (1), we obtain $I_{c0} \approx 172±18$ $\mu$A and $\ell = 26$ for Device A and $I_{c0} \approx 73±15$ $\mu$A and $\ell = 29$ for Device B after averaging the critical currents for P→AP and AP→P switching. The small critical switching currents are consistently reproduced by other devices. Considering a parallel resistor approximation, the current shunted into the FeCoB free layer and Hf spacers ($\rho_{Pt/Hf} \approx 144$ $\mu$cm, $\rho_{FeCoB} = 300$ $\mu$cm) can be estimated to be $0.2 I_{c0}$ for both devices (see Fig. S6 and Table S1). The critical switching density in the Pt spin Hall channel is therefore $I_{c0} \approx (1.0±0.1) \times 10^7$ A/cm² for Device A (no Hf spacers) and $I_{c0} \approx (3.6±0.7) \times 10^6$ A/cm² for Device B (with Hf spacers). Both the total critical switching and the low switching current density obtained from Device B are the lowest yet reported for any in-plane [2,10,11,20,26] or perpendicular [12] spin-torque MTJ (see Table 1).

![Figure 3](image-url)

**FIG. 3.** (a) Schematic of the 3-terminal MRAM device. (b) Minor loop for switching by an in-plane applied magnetic field. (c) Direct current switching loop. (d) critical current for P→AP (solid) and AP→P (open) switching as a function of current ramp rate, (e) FMR linewidth $\Delta H$ as a function of the resonance frequency $f$, (f) FMR resonance field $H_f$ for the 1.6 nm FeCoB magnetic free layers for Device A (red) and Device B (black). The solid lines in (d), (e), and (f) denote the best fits of data to Eq. (1), $H_f = H_{0f} + (2\pi/\gamma)\alpha f$, and $\gamma = (\gamma/2\pi)\sqrt{H_f (H_f + 4\pi M_{eff})}$, respectively. $H_{0f}$ and $\gamma$ are the inhomogeneous broadening of the FMR linewidth and the gyromagnetic ratio, respectively.

| SOT device | $I_{c0}$ (mA) | $j_{c0}$ (MA/cm²) | Refs |
|------------|--------------|------------------|------|
| Pt/Hf₆     | 0.073        | 3.6              | This work |
| W          | In-plane MTJ | 0.15             | [11] |
| W          | In-plane MTJ | 0.95             | [26] |
| Pt         | In-plane MTJ | 0.67             | [10] |
| Ta         | In-plane MTJ | 2.0              | [3]  |
| Pt₀₆₅Hf₀₁₅ | In-plane MTJ | 0.56             | [20] |
| Ta         | PMA MTJ      | >20              | >50  |
According to the macrospin model, \( j_{c0} \) for antidamping torque switching of an in-plane magnetized MTJ is given by

\[
j_{c0} = \frac{(2e\hbar)\mu_0 M_{t0}(H_{c}+4\pi M_{eff})/2}{\xi_{DL}} \]

where \( \mu_0 \) is the permeability of free space. The suppression of \( \mu_0 \) and the FeCoB layer. Despite this reduction, this Hf spacer decreases the effective spin mixing conductance due to the insertion of the Pt/Hf multilayer, which is still beneficial in that the attenuation and the FeCoB layer. The slight reduction of \( \xi_{DL} \) for Device B compared to Device A is attributed to the spin current attenuation and possible reduction of the effective spin mixing conductance due to the insertion of the 0.25 nm Hf layer in Device B between the Pt/Hf multilayer and the FeCoB layer. Despite this, the Hf spacer layer is still beneficial in that the suppression of \( \mu_0 \) and the reduction of \( 4\pi M_{eff} \) for the free layer interface more than compensates for the decrease in \( \xi_{DL} \). The value of \( \xi_{DL} \) ~ 0.29 for Device A is significantly higher than those previously obtained in similar studies for MRAM devices based on Pt-W (DL = 0.15)[11], Pt0.55Hf0.15 (DL = 0.098)[20], and Pt (DL = 0.12)[27]. We do not see that \( \xi_{DL} \) = 0.29 from the MRAM ramp rate experiment is ~20% less than the value determined from harmonic response measurement (Fig. 2(c)). This difference may be partly attributed to an increased magnetic damping of nanoscale devices compared to thin film stacks due to, e.g., the ion-beam damage and the side-wall oxidation of the nanopillar during the device fabrication process. Tapering of free layer was formed during the ion milling process due to the resist shielding effect (see more details in Fig. S3), which could significantly increase the effective volume of the free layer of the MRAM device and lead to additional current shunting into the free layer. This current shunting into the tapering area has not been taken into account in our calculation. For the same reasons \( \xi_{DL} \) of spin Hall materials is generally found to be underestimated in the ramp rate results of other nanoscale MRAM devices compared to in direct SOT measurements on micro-scale Hall bars [10,11,20] (e.g. for W, DL is ~0.15 from MRAM ramp rate measurements and ~0.20 from bilayer spin-torque measurements [11]).

We point out the record-low critical switching current (current density) of the SOT-MRAs based on Pt/Hf multilayers is a technologically interesting achievement. The 3-terminal SOT-MRAM is an advantageous current- and energy-efficient cache memory candidate because the separation of the read and write channels in the 3T geometry offers additional advantages over the conventional 2-terminal spin-transfer-torque geometry: e.g., unlimited endurance, faster write (sub-ns [11]), faster readout without read disturbance, lower write energy, and allowance for thick MgO barrier for enhanced TMR.

**Conclusion**

In conclusion, we have demonstrated, from direct spin-torque measurements and also spin-torque switching experiments of magnetic layers with both perpendicular and in-plane magnetic anisotropy, that introducing additional interface electron scattering within Pt by inserting sub-monolayer layers of Hf can significantly increase \( \xi_{DL} \). For example, we show an increase of \( \xi_{DL} \) from ~0.17±0.01 for a simple 4 nm-thick single Pt layer to ~0.37±0.01 for a [Pt 0.6 /Hf 0.2] /Pt 0.6 multilayer despite the attenuation of spin current from Pt by the Hf insertion layers. Taking advantage of this interface-scattering-enhanced spin Hall ratio in the Pt/Hf multilayers, we demonstrate deterministic switching of IMA FeCoB-MRAM devices with a zero-temperature critical switching current of ~73 \( \mu \)A and critical switching current density of ~3.6 \( \times 10^6 \) \( \mu \)A/cm\(^2\), both of which are the lowest values yet known. Our optimized multilayer, [Pt 0.6/Hf 0.2]/Pt 0.6 (with \( \xi_{DL} = 0.37 \), \( \rho_{xx} = 144 \) \( \mu \)Ω cm), represents a highly-efficient generator of spin-orbit torque that is also compatible with integration technology (e.g., allowing easy growth with standard sputtering techniques on Si substrates) for development of low-power magnetic memories, oscillators, and logic. Our findings also provide a new strategy with the potential to magnify SOTs generated by other heavy metals, e.g., the low-resistivity Pd-Pt [17] or Au-Pt [18].

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**References**

[1] I. 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).

[2] C. O. Avci, A. Quindeau, C.-F. Pai, M. Mann, L. Caretta, A. S. Tang, M. C. Onbasli, C. A. Ross, and G. S. D. Beach, Current-induced switching in a magnetic insulator, Nat. Mater. 16, 309–314 (2017).

[3] L. Liu, C.-F. Pai, Y. Li, H. W. Tseng, D. C. Ralph, R. A. Buhrman, Spin-torque switching with the giant spin Hall effect of tantalum, Science, 336, 555 (2012).

[4] G. Yu, P. Upadhyaya, Y. Fan, J. G. Alzate, W. Jiang, K. L. Wong, S. Takei, S. A. Bender, L.-T. Chang, Y. Jiang, M. Lang, J. Tang, Y. Wang, Y. Tserkovnyak, P. K. Amiri, and K. L. Wang, Switching of perpendicular magnetization by spin–orbit torques in the absence of external magnetic fields, Nat. Nanotech. 9, 548 (2014).

[5] V. E. Demidov, S. Urazhdin, H. Ulrichs, V. Tiberkevich,
A. Slavin, D. Baither, G. Schmitz, S. O. Demokritov, Magnetic nano-oscillator driven by pure spin current, Nat. Mater. 11, 1028 (2012).
[6] P. J. Haazen, E. Muré, J. H. Franken, R. Lavrijsen, H. J. M. Swagten, B. Koopmans, Domain wall depinning governed by the spin Hall effect, Nat. Mater. 12, 299 (2013).
[7] W. Jiang, P. Upadhyay, W. Zhang, G. Yu, M. B. Jungfleisch, F. Y. Fradin, J. E. Pearson, Y. Tserkovnyak, K. L. Wang, O. Heinonen, S. G. E. Velthuis, A. Hoffmann, Blowing magnetic skyrmion bubbles, Science 349, 283-286 (2015).
[8] O. J. Lee, L. Q. Liu, C. F. Pai, Y. Li, H. W. Tseng, P. G. Gowtham, J. P. Park, D. C. Ralph, R. A. Buhrman, Central role of domain wall depinning for perpendicular magnetization switching driven by spin torque from the spin Hall effect, Phys. Rev. B 89, 024418 (2014).
[9] L. Zhu, D. C. Ralph, R. A. Buhrman, Spin-orbit torques in heavy-metal-ferromagnet bilayers with varying strengths of interfacial spin-orbit coupling, Phys. Rev. Lett. 122, 077201 (2019).
[10] S. V. Aradhya, G. E. Rowlands, J. Oh, D. C. Ralph, R. A. Buhrman, Nanosecond-timescale low energy switching of in-plane magnetic tunnel junctions through dynamic Oersted-field-assisted spin Hall effect, Nano. Lett. 16, 5987-5992 (2016).
[11] S. Shi, Y. Ou, S.V. Aradhya, D. C. Ralph, R. A. Buhrman, Fast, Fast, low-current spin-orbit torque switching of magnetic tunnel junctions through atomic modifications of the free layer interfaces, Phys. Rev. Applied 9, 011002 (2018).
[12] M. Cubukcu et al., Ultra-fast perpendicular spin–orbit torque MRAM, IEEE Trans. Magn. 54, 9300204 (2018).
[13] S. Fukami, T. Anekawa, C. Zhang, H. Ohno, A spin–orbit torque switching scheme with collinear magnetic easy axis and current configuration, Nat. Nanotech. 11, 621-625 (2016).
[14] T. Tanaka, H. Kontani, M. Naito, T. Naito, D. S. Hirashima, K. Yamada, and J. Inoue, Intrinsic spin Hall effect and orbital Hall effect in 4d and 5d transition metals, Phys. Rev. B 77, 165117(2008).
[15] G. Y. Guo, S. Murakami, T.-W. Chen, N. Nagaosa, Intrinsic Spin Hall Effect in Platinum: First-Principles Calculations, Phys. Rev. Lett. 100, 096401 (2008).
[16] 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).
[17] L. Zhu, K. Sobotkiewich, X. Ma, X. Li, D. C. Ralph, R. A. Buhrman, Strong damping-like spin-orbit torque and tunable Dzyaloshinskii-Moriya interaction generated by low-resistivity Pd_{1-x}Pt_{x} alloys, Adv. Fun. Mater. 10.1002/adfm.201805822 (2019).
[18] L. Zhu, D. C. Ralph, R. A. Buhrman, Efficient spin current generation by the spin Hall effect in Au_{1-x}Pt_{x}, Phys. Rev. Applied 10, 031001 (2018).
[19] M.-H. Nguyen, M. Zhao, D. C. Ralph, R. A. Buhrman, Enhanced spin Hall torque efficiency in Pt_{100-x}Al_{x} and Pt_{100-x}Hf_{x} alloys arising from the intrinsic spin Hall effect, Appl. Phys. Lett. 108, 242407 (2016).
[20] M.-H. Nguyen, S. Shi, G. E. Rowlands, S. V. Aradhya, C. L. Jermain, D. C. Ralph, R. A. Buhrman, Efficient switching of 3-terminal magnetic tunnel junctions by the giant spin Hall effect of Pt_{85}Hf_{15} alloy, Appl. Phys. Lett. 112, 062404 (2016).
[21] J. W. Lee, Y.-W. Oh, S.-Y. Park, A. I. Figueroa, G. van der Laan, G. Go,K.-J. Lee, and B.-G. Park, Enhanced spin-orbit torque by engineering Pt resistivity in Pt/Co/AIO_{x} structures, Phys. Rev. B 96, 064405 (2017).
[22] Y. Ou, C.-F. Pai, S. Shi, D. C. Ralph, R. A. Buhrman, Origin of fieldlike spin-orbit torques in heavy metal/ferromagnet/oxide thin film heterostructures, Phys. Rev. B 94, 140414(R)(2016).
[23] See supplementary materials for more details on experimental methods, structural characterization of Pt /Hf multilayers, cross-sectional STEM and EDS imaging of a MRAM device, harmonic response measurement, Current-induced switching of a perpendicular Co layer, estimation of current shunting into the MTJ free layer, current switching and ramp rate experiments, and write energy and current for SOT-MRAM devices based on different strong spin Hall metals.
[24] J. Kim, J. Sinha, M. Hayashi, M. Yamanouchi, S. Fukami, T. Suzuki, S. Mitani, H. Ohno, Layer thickness dependence of the current-induced effective field vector in Ta/CoFeB/MgO, Nat. Mater. 12, 240-245(2013).
[25] C. O. Avci, K. Garello, M. Gabureac, A. Ghosh, A. Fuhrer, S. F. Alvarado, P. Gambardella, Interplay of spin-orbit torque and thermoelectric effects in ferromagnet/normal-metal bilayers, Phys. Rev. B 90, 224427(2014).
[26] C.-F. Pai, L. Liu, Y. Li, H. W. Tseng, D. C. Ralph, R. A. Buhrman, Spin transfer torque devices utilizing the giant spin Hall effect of tungsten, Appl. Phys. Lett. 101, 122404 (2012).
[27] M.-H. Nguyen, C.-F. Pai, K. X. Nguyen, D. A. Muller, D. C. Ralph, and R. A. Buhrman, Enhancement of the anti-damping spin torque efficacy of platinum by interface modification, Appl. Phys. Lett. 106, 222402 (2015).
[28] E. B. Myers, F. J. Albert, J. C. Sankey, E. Bonet, R. A. Buhrman, D. C. Ralph, Thermally activated magnetic reversal induced by a spin-polarized current, Phys. Rev. Lett. 89, 196801(2002).
[29] J. Z. Sun, Spin-current interaction with a monodomain magnetic body: A model study, Phys. Rev. B 62, 570-578 (2000).