Low-field high-frequency spin-torque-oscillations in dipolarly-coupled layers driven by localized current at ferromagnetic nano-contacts

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Abstract

Excitation of spin-torque oscillations in dipole-coupled two free ferromagnetic layers by localized current density at ferromagnetic nano-contacts was investigated experimentally and with micromagnetic simulation. Oscillations possessed characteristics of optical-mode spin-waves and even at low field (less than 400 Oe) had high frequency (15 GHz), a moderate precession amplitude (2–3°), and a narrow spectral linewidth (3 MHz) due to mutual coupling of free-layers precession and presence of nano-contacts. Micromagnetic simulation showed emission of characteristic optical-mode spin-waves from disturbances generated by domain-wall oscillations at nano-contacts.
I. INTRODUCTION

Transfer of angular momentum from a dc spin-polarized current to a nano-scale ferromagnet (FM) exerts a torque, which is call Spin-Transfer Torque (STT), that can compensate intrinsic damping torque and induce stable precession of FM moment.\textsuperscript{1} When combined with a magnetoresistance effect, like giant magnetoresistance (GMR) or tunneling magnetoresistance (TMR), high-frequency voltage oscillations will be emitted, making the so-called Spin-Torque Oscillations (STO).\textsuperscript{2} The same structures can also rectify injected ac voltage at resonance.\textsuperscript{3,4} Such microwave nano-oscillators/detectors are sought after for applications like inter-/intra-chip communication, imaging\textsuperscript{5} and non-destructive testing, and lab-on-chip sensors. STOs are a suitable candidate for such a role. However, their low output power, the trade-offs between power and frequency, and weak coherence of oscillations hinder their applications compared with their semiconductor counterparts.

Direct Nano-sized Contacts (NCs) through ultra-thin alumina Nano-Oxide Layer (NOL) between FMs formed by Ion-Assisted Oxidation (IAO) method have been investigated\textsuperscript{6–10} for nano-contact magnetoresistance (NCMR) originating from spin-scattering off a confined domain-wall.\textsuperscript{11–13} There is evidence for the presence of metallic NCs by magnetoresistance and transport properties,\textsuperscript{7} transmission-electron micrographs,\textsuperscript{8,10,14} and conductive atomic force microscopy.\textsuperscript{8,9,14} However, the measured MR ratios are far below expectation, probably due to presence of non-magnetic impurities.\textsuperscript{9,14} Non-uniform current density in TMR-STO was reported to increase the amplitude of generated precessions,\textsuperscript{15,16} and reduction in linewidth.\textsuperscript{15,17,19} In NCMR-based STOs, relatively high power and narrow linewidths were reported,\textsuperscript{20–23} with oscillation behavior similar to low-TMR-STO.\textsuperscript{24}

The dynamics of free coupled FM layers has been investigated for high-frequency emission at low applied field, linewidth narrowing, and doubling of magnetization precession frequency in resistance oscillations.\textsuperscript{25,26} And it was suggested by Braganca et al.\textsuperscript{27} that the use of a low-resistance oxide barrier can result in higher output power, which suggests NOL as a candidate. In this paper, we report on the dynamics of spin-torque-induced oscillations of two-free FM layers separated by a NOL with NCs, and coupled anti-ferromagnetically by dipole-field.
II. EXPERIMENT AND SIMULATION

The film stack used was (designed thickness in nm): n-doped silicon substrate/200-nm thermally-oxidized silicon/electrode layer(Ta (5)/Cu (200)/Ta (40)/chemical-mechanical polishing)/milling (5)/Ta (3)/Ru (2)/Fe$_{50}$Co$_{50}$ (5)/Al (1.3)/IAO 20 seconds exposure time/Al (0.3)/Fe$_{50}$Co$_{50}$ (5)/Cu (10)/Ru (10), after that, films were vacuum-annealed at 270°C and 400°C for 1.5 hours each under 10-kOe magnetic field for lower Resistance-Area (RA) product and enhanced MR ratio$^9$. FeCo, Ru, and Ta were deposited by dc magnetron sputtering. Ion-beam sputtering was used for Cu and Al deposition, with an Ar$^+$ assist-ion-gun used for IAO, in the deposition system described before$^9$. Current-Perpendicular-to-Plane (CPP) pillars of elliptical cross-section were patterned using Ar$^+$ ion-milling and electron-beam lithography. RA was found from the slope of 4-probe dc resistance vs. area inverse (1/A) line, and compared with Current-In-Plane-Tunneling (CIPT) measurement of unpatterned films. The pillar was biased through the dc arm of a bias-T and the rf port was connected to a spectrum analyzer through a 35-dB wide-band low-noise amplifier to measure the microwave STOs. The amplifier gain was subtracted from the measurement, but cable and reflection losses were not accounted for. The bottom and top electrodes design was not optimized for microwaves propagation and had an overlap area of 20 µm × 40 µm. The positive current was defined to be electrons flowing up, whereas the applied field angle ($\xi$) is defined positive clockwise from the major axis of the ellipse which points along annealing field direction. Geometry, angles and coordinates definitions are summarized in Fig. 1(a). We are presenting the detailed measurements of a 320 nm × 160 nm pillar at $\xi = 60^\circ$. Results presented later were qualitatively similar among samples. Micromagnetic simulation were conducted by finite-element-method Nmag software,$^{29}$ to understand the effect of NCs on the dynamics of STO. The geometry used is two 1-nm separated elliptic cylinders of 320×160×5 nm$^3$ dimensions. Material parameters used are: stiffness constant of 2.3 × 10$^{-10}$ erg/cm³, saturation magnetization of 1930 emu/cm$^3$,$^{30}$ with Gilbert damping constant of 0.02, and an unphysical spin polarization of 100%. The effect of NCs was simulated by including 1-nm-radius cylindrical contacts between the two layers. For hysteresis loops 20 randomly-placed NCs were added and $\xi$-dependence was calculated, whereas for qualitative understanding of STO dynamics, 4 NCs and 250-Oe field applied at 60° were used. The current profile was approximated to be confined in NCs with con-
finement extending 1 nm away from middle of NC into FM layers, as most of the voltage drop will be on this region\textsuperscript{22}, although more accurate representation is needed\textsuperscript{22}. The total current used was +17.5 mA and the current distribution was calculated by assuming that a single NC and tunnel barrier resistances are 600Ω and 500Ω, respectively\textsuperscript{8}. Oersted field was not included since it does not have an effect on the dynamics mentioned afterwards.\textsuperscript{33}

### III. RESULTS AND DISCUSSION

#### A. Resistance-field hysteresis

RA product from R-1/A plot (CIPT) was 0.2 (0.3) Ω · µm\textsuperscript{2}. Figure 1(b) shows the two-probe resistance vs. magnetic field (R-H) applied at ξ = 0° and 60° measured at the same place where the microwave measurements were conducted. The bias dependence of 4-probe differential resistance at parallel magnetization state (Fig. 1(b) inset) is relatively flat, indicating that conduction is dominated by transport through NCs and less through the tunneling barrier. The resistance temperature dependence of similarly conditioned films show metallic-transport character. Due to large size of the pillar, switching near zero field from P to AP state occurs by domain formation and a gradual rotation of magnetization. Interlayer coupling field ($H_{ic}$) can be estimated to be 400 Oe from the switching fields of easy-axis R-H. Determining the dipolar fields is complicated by the non-uniform rotation before switching and the exchange coupling through NCs favoring P alignment. Although the geometry is not azimuthally symmetric, due to large pillar size estimation agrees with the calculation of cross-demagnetization factor\textsuperscript{34} $\rho_{12} = 0.0197$ resulting in $H_{ic}$ of $4\pi \rho_{12} M_s = 433$ Oe, where $M_s$=1750 emu/cm\textsuperscript{3} is the saturation magnetization measured by magnetometry. This gives a bilinear coupling energy ($J = -2dM_s H_{ic}$, defined negative for anti-parallel coupling) of -0.7 erg/cm\textsuperscript{2}\textsuperscript{35}. Micromagnetic simulation confirmed the reduction of AP-to-P switching field by coupling through 20 NCs, and the more uniform scissoring of two layers magnetization directions at 60° compared with 0° which switching behavior is spin-flop-like with anti-parallel-coupled curled domains (Fig. 1(c)). We chose for presentation the pillar that had the closest R-H curve to micromagnetics simulation, which had 11.1% MR ratio and 0.17 Ωµm\textsuperscript{2} RA product. Other pillars’ R-H curve shapes did not have the exact switching profile indicating that fabrication damage and edge roughness had an effect on
magnetization reversal process.

B. Oscillation characteristics

The characteristics of STOs are summarized in Fig. 2. Largest power microwave oscillations were observed at \( \approx 15 \) GHz when applying high currents for \( \xi = 60^\circ \) in which the magnetization switching occurred as a single domain rotation. Sample power spectrum with a Lorentzian peak fitting is shown in Fig. 2(a). There is a drop in resistance at \( I_{dc} = 14.7 \) mA (27.5 mA) accompanied with a jump in oscillation frequency, \( f_{osc} \), a narrowing in full-width-at-half-maximum of Lorentzian-peak fitting, \( \Delta f \) and increase in integrated power, \( P_{int} \), indicating a change into auto-oscillation mode\(^{36} \), with a mechanism similar to STOs based on pin-hole tunnel junctions (Fig. 2(c)).\(^{15} \) Linear fits to normalized inverse power, \( 1/p \), at sub-threshold gave a threshold current, \( I_{th} \) of 14.74 mA for \( \xi = 60^\circ \). The highest oscillation power was 0.4 nW (1.6 nW if corrected for impedance mismatch measured with a network analyzer) giving a precession amplitude (\( \theta_p \)) of 2–3\(^\circ \), whereas the lowest \( \Delta f \) is 3 MHz corresponding to a quality factor of 5000.

Considering the mode of generated oscillations, there are two possible modes of coupled oscillations or spin-waves in two layers of free spins, with the optical (anti-phase) mode having higher frequency than the acoustic (in-phase) mode in low field region, and optical-mode frequency having large dependence on the coupling strength and relative angle between the layers, whereas the acoustic mode is mostly dependent on applied and demagnetization fields.\(^{37} \) The frequency of optical and acoustic modes can be found from the solution to coupled Bloch equations of the two layers with effective field determined from the free energy.\(^{35,37,38} \) By considering only the main contributions of Zeeman energy, film demagnetization, and interlayer exchange coupling (through dipolar fields in present case) to free energy, the optical and acoustic eigen-frequencies of an in-plane magnetization precession can be simplified to:

\[
\left( \frac{f_{ac}}{\gamma/2\pi} \right)^2 = \left( H \cos \psi + 4\pi M_s - 2H_{ic} (\cos \Delta \theta + 1) \right) \left( H \cos \psi + 8H_{ic}^2 \cos \Delta \theta \right),
\]

\[
\left( \frac{f_{op}}{\gamma/2\pi} \right)^2 = \left( H \cos \psi + 4\pi M_s - 2H_{ic} (\cos \Delta \theta + 1) \right) \left( H \cos \psi - 4H_{ic} \cos \Delta \theta \right),
\]

where \( \gamma/2\pi = 2.8 \) MHz/Oe, \( H, \psi, \) and \( \Delta \theta \) are the gyromagnetic ratio, applied magnetic field, angle between applied field and magnetization, and average relative angle between the
two magnetizations, respectively. Because the optical mode oscillations are out-of-phase, they result in higher dynamic resistance change compared to acoustic mode. Also, optical mode excitation is more stable compared to acoustic one. We confirmed the presence of the weaker-power acoustic mode (Fig. 2(b)). Using $H_{ic} = 400$ Oe and $\Delta \theta = 130–150^\circ$ from measured R-H and micromagnetic simulation gives $f_{op}$ of 14.0–16.1 GHz and $f_{ac}$ of 3.9–3.5 GHz, which agrees with the observed spectrum. The frequency of optical mode depends mostly on the coupling strength and relative angle between the layers (the last term on right in Eq. 1b). The weak dependence of $f_{osc}$ against $I_{dc}$ and $H$ (≈−1.3 MHz/Oe not shown) supports that $f_{osc}$ is determined mainly by excitation of an optical-mode spin-wave. The maximum $f_{osc}(H = 0, \Delta \theta = 180^\circ)$ from other devices was 17.8 GHz which corresponds to $H_{ic} = 460$ Oe, in agreement with the estimation from R-H curve. The sensitive dependency of optical mode frequency on $H_{ic}$ and $\Delta \theta$ explains the variation of $f_{osc}$ among devices. A more detailed study on $f_{osc}$ distribution dependence on fabrication process is needed to have better controllability on application devices. At negative current no oscillations were observed, which is unexpected for a symmetric structure, but the different magnetization angle for each layer under an inclined magnetic field make the structure asymmetric. The absence of oscillations at negative current is due to change of stable oscillations at low field from optical to acoustic mode after reversing current polarity. At high field, magnetizations become parallel, which stops oscillation. The presence of two frequency branches at sub-threshold and high-current regions can be ascribed to edge and center modes in elliptical geometries due to difference of $\Delta \theta$ at center and edges.

The linewidth broadening of STOs compared to linear auto-oscillators is understood to be due to amplitude-phase coupling, which is expressed by the nonlinearity parameter ($\nu$), and $\Delta f \propto (1+\nu^2)/p^{12}$ The $\Delta f$-1/p slopes were 3.8 and 19.4 MHz/(mA²·µW) for above-threshold and below-threshold regimes, respectively. The nonlinearity cannot be found similar to Kudo et al. probably due to the sudden change into a single excitation mode at threshold. We can calculate the nonlinearity from $\nu = (I_{dc}/\Gamma_g)(df/dI_{dc})$, where the natural FMR linewidth ($\Gamma_g$) is obtained from linear extrapolation of $\Delta f$ to zero current at sub-threshold and found to be 934 MHz. The agility of oscillation frequency in current ($df/dI_{dc}$) was $\approx −9.6$ MHz/mA, resulting in $\nu \approx −0.16$, which is one order of magnitude smaller than other reported values. A more accurate estimation based on phase noise measurement might be needed, since deviations of low-TMR-STOs has been reported. NCMR-STO usually
showed relatively small agility (16–18 MHz/mA)\cite{20,22,24} compared with other TMR-STO, leading to smaller nonlinearity and narrower linewidth. However, the coupled oscillations of two layers\cite{20,28,46}, and the tilted magnetization angle away from easy axis\cite{47} lowered agility and nonlinearity more for this report.

C. Oscillation micromagnetics

Micromagnetic simulation in the case of no NCs (upper part in Figs. 3(a–c)) had a similar oscillation frequency to the calculated and measured ones, with the optical mode being the dominant component. But precession amplitude ($\theta_p = 0.05^\circ$) is very small compared with the experimental value ($2\ldots3^\circ$). The insertion of 4 uniformly-spaced NCs increased $\theta_p$ to $2^\circ$ (lower part in Fig. 3(a–c)) with optical spin-waves emitted from NCs (Fig. 3(d)). The simulated time of NC-driven oscillations was short (20 ns) to conclude about phase-locking of NC-driven oscillations. Also in the real device the higher number of NCs ($\approx20$) means that inter-NC coupling is stronger leading to mutual phase-locking\cite{35} and the emission of a single-frequency spin wave. The required verification is beyond the scope of this work. The mechanism of spin-wave emission from NCs is of similar origin to previous reports\cite{33,49}. The domain-wall is pushed outside NC-region into the ferromagnetic layer and starts to oscillate between Néel and Bloch walls high-frequency oscillations (250 GHz for the chosen geometry and current density)(Fig. 3(e)). These very high frequency oscillations were localized up to 10 nm away from NC (Fig. 3(f)). The localized precession act as a spatial pulse which is wide in spectrum, then results in the generation of propagating spin-waves at the characteristic frequency and k-vector of the system which is an optical spin-wave in this case. This is similar to the report by Arai et al\cite{33} where they reported strongly attenuated spin-wave around the NC that is the result of domain-wall precession. But in contrast to their report, we found an excitation at the characteristic mode of the extended magnetic layers. Such a mechanism has implications on the nature of current-induced dynamics; magnetization precession is not induced by STT directly. In Fig. 2(c), going above $I_{th}$, first localized STT increases amplitude, compensates damping around NCs and increases local precession amplitude. When local precession amplitude saturates, at $I = 15.6$ mA, increase of current and STT will not change $\theta_p$, leading to loss of agility and narrowing of linewidth. At this stable regime magnetic layers act as a resonator that is excited by the energy coming from the spatial pulse.
at NCs. This makes the presented oscillator similar to a classical auto-oscillator, and results in a considerable reduction in non-linearity. Experimental confirmation of high-frequency precession at NCs is difficult using direct microwave measurement of oscillation spectrum. Homodyne-detection means with millimeter-wave or optical excitation are probably more feasible.

IV. CONCLUSIONS

We presented the measured spin-torque-driven oscillations of a spin-torque oscillator with nano-contacts between two free ferromagnetic layers coupled antiferromagnetically with dipolar-field. Resulting oscillation character agrees with propagating optical-mode spin-waves. Micromagnetic simulation result, without NCs incuded, agreed with optical-mode discussion, but the amplitude of precession was two orders of magnitude smaller than experimental value. Inclusion of NCs with localized current density showed a precession amplitude close to experimental value. Since the precession angle is smaller than angle away from anti-parallel configuration, frequency-doubling of resistance oscillations was not observed, for which we aimed using this structure. Micromagnetic simulation showed that DWs were pushed outside confinement region in NCs and started to oscillate at the adjacent layer. This excited optical-mode spin-waves to propagate away from NCs. Due to short simulation time and low density of NCs, no signs of mutual synchronization were observed during simulation, but there were only single narrow peaks in experimental spectra. We expect that ferromagnetic layers act as a resonator excited by spatial pulses at localized-current regions. This can explain the small non-linearity and narrowing of linewidth common in NCMR and pin-hole-TMR STOs. So, by utilizing NCs and tuning dipole coupling and magnetization angles, we expect to increase both power and quality factor, with frequency-multiplication in generated microwave voltage for over-40-GHz oscillations at low applied fields, which is currently under investigation.

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1. J. C. Slonczewski, “Electronic device using magnetic components,” U.S. Patent No. 5,695,864 (1997).
2. S. I. Kiselev, J. C. Sankey, I. N. Krivorotov, N. C. Emley, R. J. Schoelkopf, R. A. Buhrman, and D. C. Ralph, *Nature* **425**, 380–383 (2003).
3. A. A. Tulapurkar, Y. Suzuki, A. Fukushima, H. Kubota, H. Maehara, K. Tsunekawa, D. D. Djayaprawira, N. Watanabe, and S. Yuasa, *Nature* **438**, 339 (2005).
4. S. Miwa, S. Ishibashi, H. Tomita, T. Nozaki, E. Tamura, K. Ando, N. Mizuochi, T. Saruya, H. Kubota, K. Yakushiji, T. Taniguchi, H. Imamura, A. Fukushima, S. Yuasa, and Y. Suzuki, *Nature Materials* **13**, 50 (2014).
5. L. Fu, W. Lu, D. R. Herrera, D. F. Tapia, Y. S. Gui, S. Pistorius, and C. Hu, *Applied Physics Letters* **105**, 122406 (2014).
6. H. Fukuzawa, H. Yuasa, S. Hashimoto, K. Koi, H. Iwasaki, M. Takagishi, Y. Tanaka, and M. Sahashi, *IEEE Transactions on Magnetics* **40**, 2236 (2004).
7. H. N. Fuke, S. Hashimoto, M. Takagishi, H. Iwasaki, S. Kawasaki, K. Miyake, and M. Sahashi, *IEEE Transactions on Magnetics* **43**, 2848 (2007).
8. M. Takagishi, H. N. Fuke, S. Hashimoto, H. Iwasaki, S. Kawasaki, R. Shiozaki, and M. Sahashi, *Journal of Applied Physics* **105**, 07B725 (2009).
9. Y. Shiokawa, M. Shiota, Y. Watanabe, T. Otsuka, M. Doi, and M. Sahashi, *Magnetics, IEEE Transactions on* **47**, 3470 (2011).
10. H. Yuasa, M. Hara, Y. Fuji, and H. Fukuzawa, *EPL (Europhysics Letters)* **101**, 47005 (2013).
11. L. R. Tagirov, B. P. Vodopyanov, and K. B. Efetov, *Physical Review B* **63**, 104428 (2001).
12. J. Sato, K. Matsushita, and H. Imamura, *Journal of Applied Physics* **105**, 07D101 (2009).
13. H. Imamura and J. Sato, *Journal of Physics: Conference Series* **266**, 012090 (2011).
14. M. Al-Mahdawi and M. Sahashi, *Applied Physics Letters* **104**, 032405 (2014).
15. D. Houssameddine, S. H. Florez, J. A. Katine, J. Michel, U. Ebels, D. Mauri, O. Ozatay, B. Delaet, B. Viala, L. Folks, B. D. Terris, and M. Cyrille, *Applied Physics Letters* **93**, 022505 (2008).
16 H. Maehara, “Oscillator element and method for producing the oscillator element,” U.S. Patent App. 13/706,172 (2013).
17 D. Houssameddine, U. Ebels, B. Dieny, K. Garelo, J. Michel, B. Delaet, B. Viala, M. Cyrille, J. A. Katine, and D. Mauri, [Physical Review Letters 102, 257202 (2009)].
18 T. Devolder, L. Bianchini, J. Kim, P. Crozat, C. Chappert, S. Cornelissen, M. O. d. Beeck, and L. Lagae, [Journal of Applied Physics 106, 103921 (2009)].
19 K. Kudo, T. Nagasawa, R. Sato, and K. Mizushima, [Journal of Applied Physics 105, 07D105 (2009)].
20 H. Endo, T. Tanaka, M. Doi, S. Hashimoto, H. N. Fuke, H. Iwasaki, and M. Sahashi, [IEEE Transactions on Magnetics 45, 3418 (2009)].
21 Y. Suzuki, A. A. Tulapurkar, and C. Chappert, in [Nanomagnetism and Spintronics], edited by T. Shinjo (Elsevier, Amsterdam, 2009) pp. 93–153.
22 H. Suzuki, T. Nakamura, H. Endo, M. Doi, H. Tsukahara, H. Imamura, H. N. Fuke, S. Hashimoto, H. Iwasaki, and M. Sahashi, [Applied Physics Letters 99, 092507 (2011)].
23 M. Doi, H. Endo, K. Shirafuji, S. Kawasaki, M. Sahashi, H. N. Fuke, H. Iwasaki, and H. Imamura, [Journal of Physics D: Applied Physics 44, 092001 (2011)].
24 M. Al-Mahdawi, M. Doi, S. Hashimoto, H. N. Fuke, H. Iwasaki, and M. Sahashi, [IEEE Transactions on Magnetics 47, 3380 (2011)].
25 T. Seki, H. Tomita, T. Shinjo, and Y. Suzuki, [Applied Physics Letters 97, 162508 (2010)].
26 T. Moriyama, G. Finocchio, M. Carpentieri, B. Azzerboni, D. C. Ralph, and R. A. Buhrman, [Physical Review B 86, 060411 (2012)].
27 P. M. Braganca, K. Pi, R. Zakai, J. R. Childress, and B. A. Gurney, [Applied Physics Letters 103, 232407 (2013)].
28 T. Nagasawa, K. Kudo, H. Suto, K. Mizushima, and R. Sato, [Applied Physics Letters 105, 182406 (2014)].
29 T. Fischbacher, M. Franchin, G. Bordignon, and H. Fangohr, [Magnetics, IEEE Transactions on 43, 2896 (2007)].
30 K. Miyake, Y. Okutomi, H. Tsukahara, H. Imamura, and M. Sahashi, [Applied Physics Express 6, 113001 (2013)].
31 A. G. M. Jansen, A. P. v. Gelder, and P. Wyder, [Journal of Physics C: Solid State Physics 13, 6073 (1980)].
32 N. Strelkov, A. Vedyayev, N. Ryzhanova, D. Gusakova, L. D. Buda-Prejbeanu, M. Chshiev, S. Amara, N. de Mestier, C. Baraduc, and B. Diény, Physical Review B 84, 024416 (2011).
33 H. Arai, H. Tsukahara, and H. Imamura, Applied Physics Letters 101, 092405 (2012).
34 O. Dmytriiev, T. Meitzler, E. Bankowski, A. Slavin, and V. Tiberkevich, Journal of Physics: Condensed Matter 22, 136001 (2010).
35 M. Grimsditch, S. Kumar, and E. E. Fullerton, Physical Review B 54, 3385 (1996).
36 A. Slavin and V. Tiberkevich, Magnetics, IEEE Transactions on 45, 1875 (2009).
37 J. F. Cochran, J. Rudd, W. B. Muir, B. Heinrich, and Z. Celinski, Physical Review B 42, 508 (1990).
38 R. Zivieri, L. Giovannini, and F. Nizzoli, Physical Review B 62, 14950 (2000).
39 K. Kudo, T. Nagasawa, H. Suto, T. Yang, K. Mizushima, and R. Sato, Journal of Applied Physics 111, 07C906 (2012).
40 A. M. Deac, A. Fukushima, H. Kubota, H. Maehara, Y. Suzuki, S. Yuasa, Y. Nagamine, K. Tsunekawa, D. D. Djayaprawira, and N. Watanabe, Nature Physics 4, 803 (2008).
41 J. Kim, V. Tiberkevich, and A. N. Slavin, Physical Review Letters 100, 017207 (2008).
42 V. S. Tiberkevich, A. N. Slavin, and J. Kim, Physical Review B 78, 092401 (2008).
43 B. Georges, J. Grollier, V. Cros, A. Fert, A. Fukushima, H. Kubota, K. Yakushijin, S. Yuasa, and K. Ando, Physical Review B 80, 060404 (2009).
44 L. Bianchini, S. Cornelissen, J. Kim, T. Devolder, W. v. Roy, L. Lagae, and C. Chappert, Applied Physics Letters 97, 032502 (2010).
45 M. Quinsat, D. Gusakova, J. F. Sierra, J. P. Michel, D. Houssameddine, B. Delaet, M. Cyrille, U. Ebels, B. Diény, L. D. Buda-Prejbeanu, J. A. Katine, D. Mauri, A. Zeltser, M. Prigent, J. Nallatamby, and R. Sommet, Applied Physics Letters 97, 182507 (2010).
46 D. Gusakova, M. Quinsat, J. F. Sierra, U. Ebels, B. Diény, L. D. Buda-Prejbeanu, M. Cyrille, V. Tiberkevich, and A. N. Slavin, Applied Physics Letters 99, 052501 (2011).
47 K. Mizushima, T. Nagasawa, K. Kudo, Y. Saito, and R. Sato, Applied Physics Letters 94, 152501 (2009).
48 T. Kendziorczyk, S. O. Demokritov, and T. Kuhn, Physical Review B 90, 054414 (2014).
49 K. Matsushita, J. Sato, H. Imamura, and M. Sasaki, Journal of Physics: Conference Series 200, 042016 (2010).
FIG. 1. (a) A schematic of the elliptical pillar geometry and definitions of coordinates and angles. (b) Two-probe resistance vs. field applied at $\xi = 0^\circ$ and $60^\circ$. Inset shows the bias dependence of differential resistance in parallel magnetizations state. (c) Normalized MR found from micromagnetics simulation, for the cases of no NCs (dashed lines), and with 20 NCs (solid lines).
FIG. 2. (a) Representative oscillation power spectrum under high current at $\xi = 60^\circ$ with Lorentzian peak fitting (solid line). (b) The acoustic mode and optical mode of coupled oscillations were observed near 3 GHz and 15 GHz, respectively. (c) Current dependencies of oscillation characteristics. Same symbols in $f_{\text{osc}}$ and $\Delta f$ panels correspond to each other.
FIG. 3. Comparison of micromagnetic dynamics with or without NCs at $H = 250$ Oe, $\xi = 60^\circ$, $I_{dc} = 17.5$ mA. (a) Normalized magnetization’s y-component of the total system ($m_y$) showing that with NCs oscillations are bigger in amplitude. (b) Magnetization angle of each layer at the center of the pillar oscillating anti-phase, and NCs-STO has larger dynamic angle. (c) Fast-fourier-transformed $m_y$ of 250-ns duration of no-NCs dynamics, and 15-ns duration of NCs dynamics. (d) Snapshots of optical-mode spin-waves emitted from NCs. The color bar represents $(m_y(r, t) - m_y(r, 0))$. Up to 20-ns of simulation time, phase-locking of oscillations was not observed. (e) The confined domain-wall is pushed into ferromagnetic layer and 250-GHz precession occurs. (f) Spatial distribution of power of localized precession around the NC (sliced around the NC at $y = +40$ nm).