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Note: Electrical detection and quantification of spin rectification effect enabled by shorted microstrip transmission line technique

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We describe a shorted microstrip method for the sensitive quantification of Spin Rectification Effect (SRE). SRE for a Permalloy ($Ni_{80}Fe_{20}$) thin film strip sputtered onto SiO_2 substrate is demonstrated. Our method obviates the need for simultaneous lithographic patterning of the sample and transmission line, therefore greatly simplifying the SRE measurement process. Such a shorted microstrip method can allow different contributions to SRE (anisotropic magnetoresistance, Hall effect, and anomalous Hall effect) to be simultaneously determined. Furthermore, SRE signals from unpatterned 50 nm thick Permalloy films of area dimensions 5 mm × 10 mm can even be detected. © *2014 AIP Publishing LLC*. [http://dx.doi.org/10.1063/1.4865122]

The Spin Rectification Effect[1–6] (SRE) refers to the generation of DC voltages through the nonlinear couplings between the microwave excitation fields, spins precession, and induced oscillating charge currents. In a ferromagnet with conductivity σ and equilibrium magnetization $\vec{M}$, the time-averaged current produced due to a microwave field with dynamic component $\vec{h}$ is given by

$$\vec{I}_{DC} = -\frac{\sigma \Delta\rho}{M^2}[\langle \vec{j} \times \vec{m}\rangle \times \vec{M} + \langle \vec{j} \cdot \vec{m}\rangle \vec{M}] + \sigma R_{HE}\langle \vec{j} \times \vec{h}\rangle + \sigma R_{AHE}\langle \vec{j} \times \vec{m}\rangle, \quad (1)$$

where $\Delta\rho$ is the change in resistance due to Anisotropic Magnetoresistance (AMR), R_{HE} and R_{AHE} are the ordinary and anomalous Hall coefficients, respectively, and $\vec{j}$ and $\vec{m}$ are the AC current and magnetization, respectively. Due to its great sensitivity, SRE has become a powerful tool to study spin dynamics, such as ferromagnetic resonance (FMR),[7–13] spin waves,[14–18] and domain wall resonances.[16,19,20] A detailed understanding of SRE is also required for experiments involving the electrical detection of spin current phenomena such as Spin Hall effect,[21–29] spin torque transfer,[30–32] and spin pumping,[25,33–35] where it is often required to unambiguously distinguish SRE signals from the signal of interest. One interesting study enabled by high sensitivity SRE is the nonlinear FMR in the high microwave power regime,[15,19,20,36] where foldover effects are directly observed and studied. Such studies would be important for the understanding of nonlinear magnetization dynamics such as microwave-assisted switching.[37–40] Furthermore, SRE is highly sensitive to the relative phase between the microwave field and responding spin precession (FMR phase ϕ) as well as the relative phase Φ between the dynamic electric and magnetic components of the microwave, a fundamental property which still eludes a complete understanding thus far. Following a Spintronic Michelson Interferometry experiment[41] which allowed direct Φ probing and imaging, subsequent recent experiments[42,43] have demonstrated the potential of this powerful phase resolving ability of SRE.

Depending on sample-microwave coupling geometry, AMR, anomalous Hall effect (AHE), and Hall effect (HE) can contribute to the measured voltage, as dictated by (1). Two specific configurations are first proposed and discussed in Refs. 2 and 19 for a coplanar waveguide (CPW). Utilizing such a CPW structure offers several advantages, such as a frequency sweep analysis as well as being compact. However, this method requires films to be grown either on the CPW substrate or the signal line, thus films which are grown on complex substrates may not be suitable in such a structure. Further considerations include proper design dimensions order to ensure impedance matching to minimize power reflection. This is quite crucial since the detected DC voltage is proportional to the microwave power. Other than a CPW structure, a recent study[5] has measured the SRE in a microstrip-like structure with transverse electrical contacts.

In this note, we describe a shorted microstrip transmission line technique to detect rectified DC voltages from SRE. We demonstrate the viability and sensitivity of our method by measuring SRE in a 50 nm thick Py strip of around 1 mm width and 10 mm length, deposited onto 0.5 mm thick SiO_2 substrate of 10 mm length and 5 mm width. Our method is non-destructive to the thin film sample as it does not require the sample to be physically integrated into the microstrip transmission line for sample-microwave coupling. The sample orientation could be freely changed to allow various SRE contributions to be measured. It allows the sample to be grown on any desired substrates without worrying about any resulting significant microwave power reflection due to impedance mismatches between the microwave source and microstrip line. Based on S_{11} measurements with a network analyzer, we find that the insertion of an unpatterned Py sample only changes the power reflection coefficient by 2% at 2 GHz. Our technique also obviates the need for precise and troublesome lithographic patterning of the sample and transmission line to ensure strong sample-microwave coupling. Furthermore, this method allows a comparative study between transmission line and electrical methods to detect FMR, since it is based on our earlier method for AC permeability measurements.[44]

As discussed in Ref. 44, our 50-Ω microstrip fixture consists of a brass casing connected to ground, with one end of the microstrip shorted to casing. The sample can be placed in the air gap between the line and ground, at any position along the fixture length. Based on simulations using Ansoft HFSS, a microwave source into the fixture will generate $\vec{h}$ predominantly in-plane ($\vec{h}_{\parallel}$) and along the width of the microstrip line, which is used as the primary excitation field for SRE. The AC microwave current $\vec{j}$ lies mainly along the microstrip length. The sample is inserted into the fixture and an in-plane external bias field $\vec{H}$ is applied using a Helmholtz coil. The field configurations for the sample are as shown in Fig. 1. A SMB100A Rohde & Schwarz analogue signal generator is used as our microwave source into the fixture via the SMA connector. With power fixed at 18 dBm, a Stanford SR830 lock-in amplifier is used to detect the SRE voltages after amplitude modulation at 10 kHz provided by a Stanford DS335 function generator. For our field configurations, the SRE voltage V_{DC} can be found by Eq. (1) to be

$$V_{DC} = \frac{1}{2}|\vec{j}||\vec{h}_{\parallel}| \sin\phi_H \left\{ \frac{\Delta\rho}{M_0} A_{xx} \cos 2\phi_H [D\cos\Phi - L\sin\Phi] - R_{EH} A_{xy} [L\cos\Phi + D\sin\Phi] \right\}, \quad (2)$$

where A_{xx} and A_{xy} are components of the AC susceptibility $[\chi]$ defined by $[\chi] = (D + iL)[A]$, $D = 2\Delta H(H - H_r)/[4(H - H_r)^2 + \Delta H^2]$ and $L = \Delta H^2/[4(H - H_r)^2 + \Delta H^2]$ represent the dispersive and lorentzian lineshapes, respectively. H_r and ΔH are the FMR field and FMR linewidth, respectively. Therefore, our SRE voltage consists of contributions from both AMR and AHE, each with different ϕ_H dependences. In our measurement, we fix ϕ_H at 45° so only the AHE contribution is non-zero, that is,

$$V_{DC,45^\circ} = -\frac{\sqrt{2}}{4} R_{EH} |\vec{j}||\vec{h}| A_{xy} [L\cos\Phi + D\sin\Phi]. \quad (3)$$

Our measured $V_{DC,45^\circ}$ will be a combination of L and D lineshapes at FMR, whose relative contributions depend strongly on the relative phase Φ. For a Py strip of 1 mm width, Fig. 2 shows the measured voltage as a function of H for various frequencies. Clear peak shifts with lineshape transitions between lorentzian and dispersive are observed. These lineshape transitions with frequency, which have been commonly observed,[3,5,6,12,13,18,25,45] have been attributed to changes in Φ with frequency which depends strongly on material losses as well as transmission line characteristics. A detailed calculation that takes into account the sample properties and microwave propagation in the fixture will be needed to understand how Φ varies with frequency, which is beyond our current scope.

Fig. 3 shows a quantitative fit of the peak shifts with frequency. FMR occurs at the lorentzian peak positions and the dispersive positions of greatest gradient, which can be well fitted with Kittel's formula, where FMR frequency[46] $f_{FMR} = \frac{\gamma}{2\pi}\sqrt{(H + H_k)(H + H_k + 4\pi M_s)}$ with γ being the

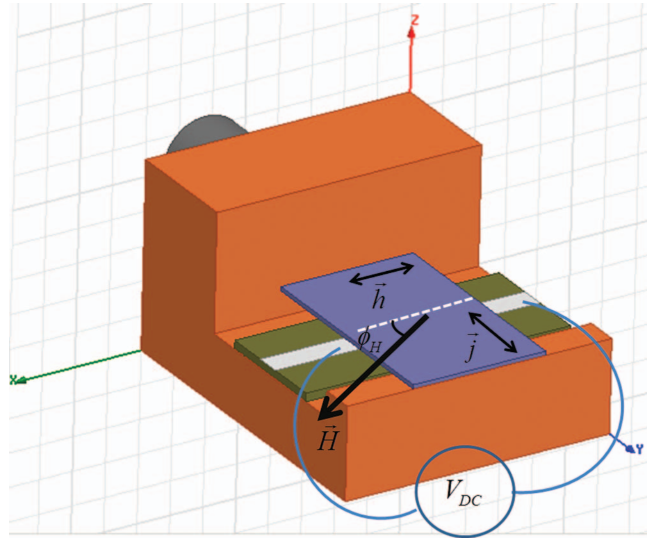

FIG. 1. Configuration for SRE measurement.

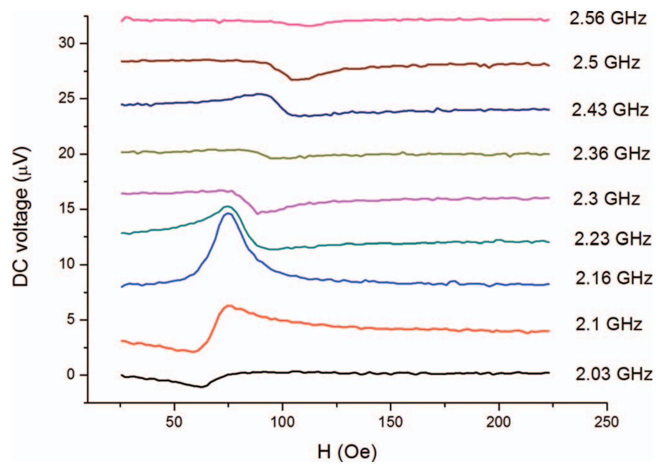

FIG. 2. SRE voltages measured at $\phi_H = 45°$, for various frequencies as a function of H. Voltages are offset for clarity.

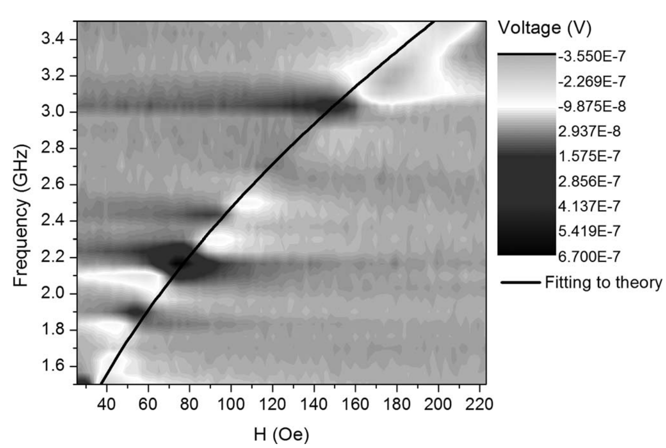

FIG. 3. 2D contour mapping of measured voltages for field sweeps at various frequencies. The solid line represents a fit to Kittel's equation.

gyromagnetic ratio, H_k is the anisotropy field, and M_s the saturation magnetization. With $H_k = 0$ for negligible anisotropy, M_s is fitted to be 7700 Oe. Finally, we note that even if the 50 nm thick Py film is directly deposited without patterning on SiO_2 substrate, SRE can also be detected for the same field configurations.

[1] H. J. Juretschke, J. Appl. Phys. **31**, 1401 (1960).
[2] Y. Gui, N. Mecking, X. Zhou, G. Williams, and C. M. Hu, Phys. Rev. Lett. **98**, 107602 (2007).
[3] N. Mecking, Y. Gui, and C. M. Hu, Phys. Rev. B **76**, 224430 (2007).
[4] Y. S. Gui, N. Mecking, A. Wirthmann, L. H. Bai, and C. M. Hu, Appl. Phys. Lett. **91**, 082503 (2007).
[5] H. Chen, X. Fan, H. Zhou, W. Wang, Y. S. Gui, C. M. Hu, and D. Xue, J. Appl. Phys. **113**, 17C732 (2013).
[6] X. F. Zhu, M. Harder, J. Tayler, A. Wirthmann, B. Zhang, W. Lu, Y. S. Gui, and C. M. Hu, Phys. Rev. B **83**, 140402 (2011).
[7] H. Chen, X. Fan, W. Wang, H. Zhou, Y. S. Gui, C. M. Hu, and D. Xue, Appl. Phys. Lett. **102**, 202410 (2013).
[8] S. Chen, M. Tang, Z. Zhang, B. Ma, S. T. Lou, and Q. Y. Jin, Appl. Phys. Lett. **103**, 032402 (2013).
[9] M. Goto, H. Hata, A. Yamaguchi, Y. Nakatani, T. Yamaoka, and Y. Nozaki, J. Appl. Phys. **109**, 07D306 (2011).
[10] M. Goto, H. Hata, A. Yamaguchi, Y. Nakatani, T. Yamaoka, Y. Nozaki, and H. Miyajima, Phys. Rev. B **84**, 064406 (2011).
[11] M. Goto, H. Hata, A. Yamaguchi, H. Miyajima, Y. Nakatani, T. Yamaoka, and Y. Nozaki, J. Phys.: Conf. Ser. **266**, 012080 (2011).
[12] X. Hui, A. Wirthmann, Y. S. Gui, Y. Tian, X. F. Jin, Z. H. Chen, S. C. Shen, and C. M. Hu, Appl. Phys. Lett. **93**, 232502 (2008).
[13] M. Harder, Z. X. Cao, Y. S. Gui, X. L. Fan, and C. M. Hu, Phys. Rev. B **84**, 054423 (2011).
[14] Y. Gui, N. Mecking, and C. Hu, Phys. Rev. Lett. **98**, 217603 (2007).
[15] M. P. Wismayer, B. W. Southern, X. L. Fan, Y. S. Gui, C. M. Hu, and R. E. Camley, Phys. Rev. B **85**, 064411 (2012).
[16] C. Boone, J. Katine, J. Childress, V. Tiberkevich, A. Slavin, J. Zhu, X. Cheng, and I. Krivorotov, Phys. Rev. Lett. **103**, 167601 (2009).
[17] Y. Gui, S. Holland, N. Mecking, and C. Hu, Phys. Rev. Lett. **95**, 056807 (2005).
[18] A. A. Tulapurkar, Y. Suzuki, A. Fukushima, H. Kubota, H. Maehara, K. Tsunekawa, D. D. Djayaprawira, N. Watanabe, and S. Yuasa, Nature (London) **438**, 339 (2005).
[19] Y. Gui, A. Wirthmann, N. Mecking, and C. M. Hu, Phys. Rev. B **80**, 060402 (2009).
[20] Y. S. Gui, A. Wirthmann, and C. M. Hu, Phys. Rev. B **80**, 184422 (2009).
[21] E. Saitoh, M. Ueda, H. Miyajima, and G. Tatara, Appl. Phys. Lett. **88**, 182509 (2006).
[22] O. Mosendz, V. Vlaminck, J. E. Pearson, F. Y. Fradin, G. E. W. Bauer, S. D. Bader, and A. Hoffmann, Phys. Rev. B **82**, 214403 (2010).
[23] Z. Feng, J. Hu, L. Sun, B. You, D. Wu, J. Du, W. Zhang, A. Hu, Y. Yang, D. M. Tang, B. S. Zhang, and H. F. Ding, Phys. Rev. B **85**, 214423 (2012).
[24] B. F. Miao, S. Y. Huang, D. Qu, and C. L. Chien, Phys. Rev. Lett. **111**, 066602 (2013).
[25] A. Azevedo, L. H. Vilela-Leão, R. L. Rodríguez-Suárez, A. F. Lacerda Santos, and S. M. Rezende, Phys. Rev. B **83**, 144402 (2011).
[26] O. Mosendz, J. E. Pearson, F. Y. Fradin, G. E. W. Bauer, S. D. Bader, and A. Hoffmann, Phys. Rev. Lett. **104**, 046601 (2010).
[27] H. Jiao and G. E. W. Bauer, Phys. Rev. Lett. **110**, 217602 (2013).
[28] Y. Kajiwara, K. Harii, S. Takahashi, J. Ohe, K. Uchida, M. Mizuguchi, H. Umezawa, H. Kawai, K. Ando, K. Takanashi, S. Maekawa, and E. Saitoh, Nature (London) **464**, 262 (2010).
[29] N. Vlietstra, J. Shan, V. Castel, J. Ben Youssef, G. E. W. Bauer, and B. J. van Wees, Appl. Phys. Lett. **103**, 032401 (2013).
[30] L. Berger, Phys. Rev. B **54**, 9353 (1996).
[31] L. Berger, J. Appl. Phys. **90**, 4632 (2001).
[32] J. C. Slonczewski, J. Magn. Magn. Mater. **159**, L1 (1996).
[33] S. M. Rezende, R. L. Rodríguez-Suárez, M. M. Soares, L. H. Vilela-Leão, D. Ley Domínguez, and A. Azevedo, Appl. Phys. Lett. **102**, 012402 (2013).
[34] Z. Qiu, K. Ando, K. Uchida, Y. Kajiwara, R. Takahashi, H. Nakayama, T. An, Y. Fujikawa, and E. Saitoh, Appl. Phys. Lett. **103**, 092404 (2013).
[35] A. Kapelrud and A. Brataas, Phys. Rev. Lett. **111**, 097602 (2013).
[36] X. Fan, E. Himbeault, Y. S. Gui, A. Wirthmann, G. Williams, D. Xue, and C. M. Hu, J. Appl. Phys. **108**, 046102 (2010).
[37] C. Thirion, W. Wernsdorfer, and D. Mailly, Nat. Mater. **2**, 524 (2003).
[38] R. Verba, G. Melkov, V. Tiberkevich, and A. Slavin, Appl. Phys. Lett. **100**, 192412 (2012).
[39] C. Nistor, K. Sun, Z. Wang, M. Wu, C. Mathieu, and M. Hadley, Appl. Phys. Lett. **95**, 012504 (2009).
[40] Z. Wang, K. Sun, W. Tong, M. Wu, M. Liu, and N. X. Sun, Phys. Rev. B **81**, 064402 (2010).
[41] A. Wirthmann, X. Fan, Y. S. Gui, K. Martens, G. Williams, J. Dietrich, G. E. Bridges, and C. M. Hu, Phys. Rev. Lett. **105**, 017202 (2010).
[42] Z. X. Cao, M. Harder, L. Fu, B. Zhang, W. Lu, G. E. Bridges, Y. S. Gui, and C. M. Hu, Appl. Phys. Lett. **100**, 252406 (2012).
[43] X. F. Zhu, M. Harder, A. Wirthmann, B. Zhang, W. Lu, Y. S. Gui, and C. M. Hu, Phys. Rev. B **83**, 104407 (2011).
[44] Y. Liu, L. Chen, C. Y. Tan, H. J. Liu, and C. K. Ong, Rev. Sci. Instrum. **76**, 063911 (2005).
[45] L. H. Bai, Y. S. Gui, A. Wirthmann, E. Recksiedler, N. Mecking, C. M. Hu, Z. H. Chen, and S. C. Shen, Appl. Phys. Lett. **92**, 032504 (2008).
[46] C. Kittel, Phys. Rev. **71**, 270 (1947).