Room-Temperature Charge-to-Spin Conversion from Quasi-2D Electron Gas at SrTiO$_3$-Based Interfaces

Utkarsh Shashank, Angshuman Deka, Chen Ye, Surbhi Gupta, Rohit Medwal, Rajdeep Singh Rawat, Hironori Asada, X. Renshaw Wang,* and Yasuhiro Fukuma*

Interfacial two-dimensional electron gases (2DEG), especially the SrTiO$_3$-based ones at the unexpected interface of insulators, have emerged to be promising candidates for efficient charge–spin interconversion. Herein, to gain insight into the mechanism of the charge–spin interconversion, quasi-2DEG between insulating SrTiO$_3$ and two types of aluminum-based amorphous insulators, namely SrTiO$_3$/AlN and SrTiO$_3$/Al$_2$O$_3$, are focused on and their charge-to-spin conversion efficiency is estimated. The two types of amorphous insulators are selected to probe the overlooked contribution of oxygen vacancy. A mechanism to explain the results of spin–torque ferromagnetic resonance measurements is proposed and an analysis protocol to reliably estimate in quasi-2DEG is developed. The resultant, thickness of the 2DEG, is estimated to be 0.244 and 0.101 nm$^{-1}$ for SrTiO$_3$/AlN and SrTiO$_3$/Al$_2$O$_3$, respectively, which are strikingly comparable to their crystalline counterparts. Furthermore, a large direct current modulation of resonance linewidth in SrTiO$_3$/AlN samples is developed, confirming and attesting an oxygen vacancy-enabled charge–spin conversion. The findings emphasize the defects’ contribution, especially in oxide-based low-dimensional systems, and provide a way to create and enhance charge–spin interconversion via defect engineering.

1. Introduction

The formation of 2D electron gas (2DEG) at oxide interfaces has attracted significant research interest owing to the presence of conduction electrons and its interesting phenomena, such as superconductivity and magnetism.$^{[1-3]}$ In addition to the observation of interfacial conductivity, the ability to achieve high carrier mobility $>$10$^5$ cm V$^{-1}$ s$^{-1}$ in 2DEGs is particularly interesting in the development of all-oxide devices.$^{[4,5]}$ Theoretical reports$^{[6-8]}$ predicted that, due to the presence of an inversion asymmetry at the interface, a 2DEG electron with momentum $\sim p$ in the presence of an electric field $\sim E$ can experience a Rashba-like field $\propto \frac{p}{E}$ in its rest frame because of spin–orbit coupling (SOC).$^{[9]}$ The possibility of achieving a strong Rashba SOC at these 2DEGs allows compatibility with spintronic devices and, therefore, has given rise to a series of experiments to understand magnetotransport in the 2DEG.$^{[10-20]}$ A large number of these investigations have been focused on spin–charge interconversion in 2DEG formed at interfaces of epitaxial LaAlO$_3$...
(LAO) and LaTiO$_3$ (LTO) films grown on single-crystalline SrTiO$_3$ (STO) substrates.$^{[15–20]}$ Recently, reports on giant room-temperature charge to spin conversion efficiency, $\theta_{cs}$ as high as 6.3 in epitaxial LAO/STO-based 2DEG,$^{[15]}$ implying that they are significantly more efficient than most heavy metals (HM)$^{[21]}$ topological insulators,$^{[22,23]}$ and engineered HM$^{[24–26]}$ toward spin current generation. Such properties position the 2DEG as an interesting candidate for applications in future spintronic devices, such as power-efficient spin–charge interconversion.

Recent reports on high mobility in systems like STO/Al$_2$O$_3$ interfaces have brought back attention toward 2DEGs formed between STO and amorphous owing to their relative ease of deposition compared to their crystalline counterparts.$^{[4,27]}$ These 2DEGs originate from oxygen vacancies in the STO side and are confined to a few nanometers (nm) inside the substrate surface. Broadly speaking, when a metal-based oxide/nitride, especially the Al-based materials, is deposited on an STO substrate, a layer of oxygen vacancies is created at the surface of STO due to the redox reactions between Al-based oxide/nitride and STO. Such oxygen vacancies lead to mobile electrons, producing an interfacial quasi-2DEG (hereafter, q-2DEG) inside STO. This leads to the creation of a conductive channel inside the STO substrate, as schematically shown in Figure 1a. Such q-2DEG induced by oxygen vacancies have often been overlooked in earlier studies and therefore we focus on potential higher charge–spin interconversion in these systems. Furthermore, although spin–charge current interconversion in 2DEG was reported at cryogenic temperatures,$^{[27]}$ a systematic analysis of such a phenomenon at room temperature is lacking. Previous studies have indicated that angular-dependent measurement of magnetization dynamics is crucial toward an accurate estimation of magnetic anisotropies and torques.$^{[26,28–31]}$ Therefore, we use such an approach to systematically investigate the charge-to-spin conversion efficiency of q-2DEG.

In this study, using spin torque ferromagnetic resonance (ST-FMR) measurements in STO/AlN/NiFe and STO/Al$_2$O$_3$/NiFe systems, we show that $\theta_{cs}$ in the q-2DEG can be as high as their crystalline counterparts at room temperature. Our experiments clearly show the presence of a symmetric component in the ST-FMR lineshape, which has an odd parity with the direction of the magnetic field, confirming the presence of spin torque in the devices. In addition to the expected $\sin^2\phi\cos\phi$ dependence of the symmetric and antisymmetric amplitudes of the ST-FMR spectra, we also detect contributions from a $\sin^2\phi\sin\phi$-like and $\sin^2\phi$-like behavior. By filtering out the $\sin^2\phi\cos\phi$ contributions of the ST-FMR spectra, we estimate $\theta_{cs}/t = 0.244$ and 0.101 nm$^{-1}$ for the STO/AlN/NiFe and STO/Al$_2$O$_3$/NiFe systems, respectively. Additionally, using DC-biased ST-FMR measurements, we show that modulation of resonant linewidth in the STO/AlN/NiFe samples is approximately three times higher than conventional HMs, that is, Pt.

**Figure 1.** a) Schematic of q-2DEG formed inside the STO substrate at the interface with AlN or Al$_2$O$_3$. Upon deposition of AlN or Al$_2$O$_3$, O$^-$ diffuses outward from the TiO$_2$-terminated STO, resulting in formation of oxygen vacancy-induced q-2DEG near the surface of STO. The right panel additionally shows the multilayer structures and different parameters used in the measurement. b) Schematic of ST-FMR set-up along with an optical image of the device. c) ST-FMR spectra, together with fit symmetric and antisymmetric components, which were obtained at $f = 4$ GHz for STO/AlN/NiFe and STO/Al$_2$O$_3$/NiFe.
directly affirming the presence of a high in-plane damping-like spin torque arising from the q-2DEG.

2. Experimental Section

A pattern of dimension $80 \times 20 \mu m^2$ was created on TiO$_x$-terminated STO (100) substrates using photolithography, wherein 10 nm AlN or Al$_2$O$_3$ was deposited using pulsed laser deposition (PLD) at room temperature at a pressure of $10^{-4}$ Pa. The sheet resistance, $R_s$, of the STO/AlN and STO/Al$_2$O$_3$ samples were around $90 \approx 10^3 \Omega \square^{-1}$, respectively. Subsequently, 5 nm NiFe was deposited using DC sputtering on the same pattern. Finally, using aligned photolithography and DC sputtering, Ti (10 nm)/Al (200 nm) electrodes were deposited on either side of the $80 \times 20 \mu m^2$ pattern to create the device, as shown in Figure 1b. See Figure S1, Supporting Information, for details of device fabrication.

Due to the SOC at the q-2DEG, a spin current is generated in the device using a signal generator while an external magnetic field $H_{ext}$ is swept in the in-plane direction. The $H_{ext}$ could be rotated in plane with respect to the $I_{rf}$, as depicted in the right panel of Figure 1a, by varying the angle $\phi$ with the $I_{rf}$. All measurements were performed at room temperature.

3. Results and Discussion

Due to the SOC at the q-2DEG, a spin current is generated in the NiFe layer. A combined effect of an alternating anisotropic magnetoresistance signal (AMR) of NiFe and the microwave current $I_{rf}$ proportional to spin current gives the ST-FMR voltage $V_{mix}$, which is recorded using a lock-in amplifier (Figure 1b). The input $I_{rf}$ is amplitude modulated by a low frequency sinusoidal wave signal. Moreover, the low frequency modulating signal serves as a trigger since it is provided as a reference signal into the reference port of lock-in amplification. Here, in the ST-FMR device as shown in Figure 1b, the modulated $I_{rf}$ is applied that leads to typical ST-FMR spectrum (voltage). Finally, ST-FMR spectrum here is the low frequency voltage (instead of DC) due to the $I_{rf}$ being amplitude modulated. The ST-FMR spectrum can be detected using the phase locking technique. A typical spectrum obtained from this measurement at a frequency of 4.0 GHz is shown in Figure 1c. This spectrum is then fit with the sum of a symmetric Lorentzian and an antisymmetric component using the following equation:

$$V_{mix} = SF_{sym}(H_{ext}) + AF_{asym}(H_{ext})$$

where $F_{sym}(H_{ext}) = \frac{(\Delta H)^2}{(H_{ext}+\Delta H)^2 + (\Delta H)^2}$ is the symmetric component with weight $S$, $F_{asym}(H_{ext}) = \frac{\Delta H (H_{ext}+\Delta H)}{(H_{ext}+\Delta H)^2 + (\Delta H)^2}$ is the antisymmetric component with weight $A$, and $\Delta H$ and $H_0$ are the half-width at half-maximum and resonance field of the FMR spectra. From the fit, we obtain $\mu_s\Delta H = 4.34$ mT for STO/AlN/NiFe and $\mu_s\Delta H = 1.71$ mT for the STO/Al$_2$O$_3$/NiFe sample at $f = 5$ GHz, which indicates lower damping for the latter sample. (also see Figure S2, Supporting Information). Meanwhile, we obtained $\mu_s H_0 = 38.54$ mT for STO/AlN/NiFe and $\mu_s H_0 = 33.59$ mT for the STO/Al$_2$O$_3$/NiFe sample at $f = 5$ GHz. Because the NiFe layers were deposited on both samples simultaneously, the difference in resonance field may be due to different effective demagnetizing fields, $M_{eff}$, in the two samples (also see the Figure S2, Supporting Information).

In addition, we also observed that, while the symmetric component magnitude is almost similar with an opposite sign with the $H_{ext}$ reversed, the antisymmetric component is different upon $H_{ext}$ reversal. The odd parity of the symmetric component with respect to the direction of the magnetic field indicates that it originates from the spin torque generated by the q-2DEG. Due to the SOC at the q-2DEG, a spin current is generated transverse to the flow of microwave current $I_{rf}$. This spin current flows from the q-2DEG to the NiFe layer and exerts a torque on the magnetization of NiFe, resulting in the symmetric component of the ST-FMR spectra. In addition, $I_{rf}$ also generates an Oersted field, $h_{rf}$, which can exert a field torque on the magnetization of NiFe layer and give rise to the antisymmetric component of the ST-FMR spectra. In order to avoid any contributions to the rectified voltage lineshape that can arise from nonlinear excitation of magnetization dynamics, we ensure that all our measurements were performed in the linear regime by checking the input power $P_{app}$ dependence of the spectra. As power increases from 0 to 13 dBm, $\Delta H$ and $H_0$ remain invariant with power, as shown in Figure S3, Supporting Information. This confirms that $V_{mix}$ is due to the excitation of the uniform FMR mode in this input power range. We performed our measurements at $P_{app} = 10$ dBm (10 mW).

Frequency-dependent measurements of the ST-FMR spectra in the range of 3.5–5 GHz for STO/AlN/NiFe and STO/Al$_2$O$_3$/NiFe samples were performed (see Figure 2). Throughout the frequency range, we observed a similar behavior of the symmetric and antisymmetric components of the ST-FMR spectra for both samples as described in the previous paragraph. The amplitude of the spectra decreases at a higher frequency. The resonance field, $H_{res}$, increases with increasing frequency, which in turn leads to a lower precession cone angle at higher $H_{ext}$. In addition, the $H_{res}$ increases with the frequency, which agrees well with the Kittel equation. Upon fitting to the Kittel equation, we obtained $\mu_s M_{eff} = 698$ mT and $814$ mT for the STO/AlN/NiFe and the STO/Al$_2$O$_3$/NiFe samples, respectively (see Figure S2, Supporting Information). This confirms that the difference in resonance fields in STO/AlN/NiFe and STO/Al$_2$O$_3$/NiFe samples arises from the different effective demagnetizing fields.

When the symmetric component of the ST-FMR spectra is attributed to a $y$-polarized spin current, $\vec{\sigma}_y$, travelling in the $z$-direction, the angular dependence of the symmetric amplitude follows a $\sin 2\phi \cos \phi$ dependence. Simultaneously, due to the flow of an $x$-axial microwave current in the device, an antisymmetric component is also produced by the corresponding Oersted field, which follows a $\sin 2\phi \cos \phi$ dependence. In this scenario, the $\theta_{cs}$ can be estimated using:

$$\theta_{cs} = \frac{S \mu_s M_{eff} A}{\hbar} \sqrt{1 + \frac{M_{eff}}{H_0}}$$

Phys. Status Solidi RRL 2023, 17, 2200377

© 2022 Wiley-VCH GmbH
where \( t \) is the q-2DEG thickness, \( e \) is the elementary charge, \( \mu_o \) is the permeability of free space, \( M_s \) is the saturation magnetization of NiFe, \( d \) is NiFe thickness, \( \hbar \) is the reduced Planck constant and \( M_{\text{eff}} \) is effective magnetization obtained from the Kittel fitting. The corresponding angular-dependent components of voltages in the STO/AlN/NiFe and STO/Al2O3/NiFe samples are plotted in Figure 3a,c, respectively. The symmetric component is fit to the following equation (see Figure S4, Supporting Information).

\[
V_s = a \sin 2\phi \cos \phi + b \sin 2\phi \sin 2\phi
\]  

(3)

where \( a \) is the weightage of the \( \sin 2\phi \cos \phi \) component and \( b \) is the weightage of the \( \sin \phi \sin 2\phi \) component. Meanwhile, the antisymmetric component is fit to

\[
V_A = c \sin 2\phi \cos \phi + d \sin 2\phi \sin \phi + \epsilon \sin 2\phi
\]  

(4)

where \( c, d, \) and \( \epsilon \) are the weights of the \( \sin 2\phi \cos \phi, \sin 2\phi \sin \phi, \) and \( \sin 2\phi \) components, respectively. We note that, in our devices, the angular dependence of symmetric and antisymmetric components is not purely \( \sin 2\phi \cos \phi \). Figure 3b,d shows the weightage of the different symmetric and antisymmetric parts of the spectra for \( f = 3.5-5 \) GHz in the case of the STO/AlN/NiFe and STO/Al2O3/NiFe samples, respectively. For STO/AlN/NiFe, the symmetric component has 95.3% \( \sin 2\phi \cos \phi \) dependence, with the rest 4.7% arising from \( \sin 2\phi \sin \phi \) dependence when averaged over the entire frequency range. Meanwhile, its antisymmetric component has an average of 49.5%, 22.5%, and 28.0% contributions from \( \sin 2\phi \cos \phi, \sin 2\phi \sin \phi, \) and \( \sin 2\phi \).
dependence, respectively. In the case of STO/Al₂O₃/NiFe, we find that the symmetric component has 75.5% sin 2ϕ cos ϕ dependence and 24.5% sin 2ϕ sin ϕ dependence averaged over the entire frequency range. On the other hand, its antisymmetric component has an average of 55.7%, 16.4%, and 27.9% contributions from sin 2ϕ cos ϕ, sin 2ϕ sin ϕ, and sin 2ϕ dependences, respectively. This indicates breaking of the twofold (180° + ϕ) and mirror (180° − ϕ) symmetries of torques for both the q-2DEG-NiFe samples. Therefore the lineshape analysis method, that is, Equation (2), which uses a spectrum obtained at a single azimuthal angle ϕ, may not reveal the comprehensive picture of torques, leading to inaccurate quantification of SOTs.[33]

Although an investigation into the exact origins of these additional components in the ST-FMR spectra is beyond the scope of this article, we would like to emphasize that we reproducibly observed this behavior in multiple devices over a wide range of frequencies. This may be a consequence of non-uniform microwave current flow in devices. In order to rule out the possibility that it is caused by our device design, we further verified the same experiments in a Pt/NiFe device fabricated under similar conditions and found 100% sin 2ϕ cos ϕ dependence for both symmetric and antisymmetric components of the ST-FMR spectra (see Figure S3, Supporting Information). NiFe has a much lower resistivity compared to the q-2DEG created at the STO/Al₂O₃ interface. This may lead to nonuniform current flow in the q-2DEG-NiFe device. In our study, we assume the 2DEG thickness, t, is shown in Figure 3, Supporting Information. The frequency dependence of the symmetric and antisymmetric components in the ST-FMR spectra for the STO/Al₂O₃/NiFe sample is noteworthy. The results are compared to previous reports on 2DEG formed in epitaxial oxides grown on STO substrates. These are comparable in terms of charge-to-spin conversion efficiencies with the 2DEG reported for the epitaxial oxides on STO. Moreover, the 2DEG in our sample is 1 or 2 orders of magnitude higher than that of HM, such as Pt,[34] Ta,[21] and also than engineered HM.[24–26] As seen from the sheet resistance values, the q-2DEG in STO/Al₂O₃ has 1 order smaller resistance values compared to STO/Al₂O₃. This indicates that when AlN is deposited over STO substrates, higher number of O²⁻ diffuse outward from the substrate to oxidize AlN compared to when Al₂O₃ is deposited. This in turn creates a larger number of oxygen defects inside the STO substrate. As demonstrated by Chen et al., this difference in diffusion may have to do with the difference in chemical reactivity of AlN and Al₂O₃ with TiO₂-terminated STO.[36] Our observation of a higher charge-to-spin conversion in the STO/Al₂O₃ samples indicates that the higher oxygen vacancies not only play a role in enhancing the electronic transport, but may also lead to a higher charge-to-spin conversion efficiency in the q-2DEG.

The modulation of damping of FMR can also be an additional tool to overcome the issues with θcs estimation mentioned in this article as it provides a direct insight into the strength of damping-like spin torques. This is free from problems arising from impedance mismatch, unconventional spin current polarized in different directions, and Nernst heating.[32] In this method, an additional direct current (DC) I dc is applied along with I rf. The spin current at the Rashba interface, which is proportional to I dc, modulates the ferromagnetic resonance linewidth (or the Gilbert damping) of NiFe via damping-like torque which has room temperature has been reported for STO/LaAlO₃/NiFe,[20] θcs ≈ 2.4 for quasi-2DEG in an STO/LaTiO₃/NiFe system,[18] and θcs ≈ 6.3 for STO/LaAlO₃/CoFeB.[15] In our case, if we assume the 2DEG thickness, t = 10 nm, and θcs comes out to be 2.44 for the STO/Al₂O₃/NiFe and 1.01 for STO/Al₂O₃/NiFe samples. These values are comparable to previous reports on 2DEG formed in epitaxial oxides grown on STO substrates. Note that the AlN and Al₂O₃ layers are amorphous in our case. Hence, θcs created at the q-2DEG in our STO/amorphous oxide interfaces are shown to be comparable in terms of charge-to-spin conversion efficiencies with the 2DEG reported for the epitaxial oxides on STO. Moreover, θcs in our sample is 1 or 2 orders of magnitude higher than that of HM, such as Pt,[34] Ta,[21] and also than engineered HM.[24–26] As seen from the sheet resistance values, the q-2DEG in STO/Al₂O₃ has 1 order smaller resistance values compared to STO/Al₂O₃. This indicates that when AlN is deposited over STO substrates, higher number of O²⁻ diffuse outward from the substrate to oxidize AlN compared to when Al₂O₃ is deposited. This in turn creates a larger number of oxygen defects inside the STO substrate. As demonstrated by Chen et al., this difference in diffusion may have to do with the difference in chemical reactivity of AlN and Al₂O₃ with TiO₂-terminated STO.[36] Our observation of a higher charge-to-spin conversion in the STO/Al₂O₃ samples indicates that the higher oxygen vacancies not only play a role in enhancing the electronic transport, but may also lead to a higher charge-to-spin conversion efficiency in the q-2DEG.

Using Equation (5), we estimated the median θcs/t to be 0.244 nm⁻¹ for the STO/AlN sample and 0.101 nm⁻¹ for the STO/Al₂O₃ sample. The frequency dependence of θcs/t is shown in Figure 4. The values of θcs/t estimated using Equation (2) are also plotted in the same figure to show the discrepancy between the two methods. Note that such a discrepancy is not seen for the Pt/NiFe devices (see Figure S5, Supporting Information).

As mentioned earlier, the calculated values in our case are normalized by the 2DEG thickness. Typically, in previous reports, the 2DEG thickness is assumed to be 10 nm, and a θcs ≈ 1.8 at...
However, we are unable to quantify width for STO/Al₂O₃/NiFe. This is due to a significant damping-like torque in STO/Al₂O₃/NiFe. The slope of linearity modulation seen for the Pt/NiFe samples, as shown in Figure 5a, indicates a reversed slope of ΔH versus I_d. Upon changing the polarity of I_d, we observe a large direct current modulation of ΔH with I_d, comparable to that of epitaxial films, is important because of the relative ease with which amorphous films can provide added functionalities in 2DEG applications.[14,16-18] Moreover, a large direct current modulation of linewidth for STO/Al₂O₃ provides direct confirmation of high θᵣ in our q-2DEG. The similarity between our amorphous and crystalline oxide interfaces in terms of charge density and conductivity along with the charge-to-spin conversion may provide insight into the microscopic mechanisms and further optimization of the conversion efficiencies. An ability to efficiently generate spin current from q-2DEG, while simultaneously understanding their angular dependent properties that shed light on the directionality of spin torques, is crucial for their implementation in spintronic device applications.

Supporting Information
Supporting Information is available from the Wiley Online Library or from the author.

Acknowledgements
U.S. and A.D. contributed equally to this work. Y.F. and H.A. would like to acknowledge JSPS Grant-in-Aid (KAKENHI no. 22K04198), KIOXIA Corporation and Iketani Science and Technology Foundation. X.R.W. acknowledges support from Academic Research Fund Tier 2 (grant no. MOE-T2EP50220-0005) and Tier 3 (grant no. MOE2018-T3-1-002) from Singapore Ministry of Education. R.M., S.G., and R.S.R. would like to acknowledge the support from the National Research Foundation (NRF), Singapore, under its 21st Competitive Research Programs (CRP grant no. NRF-CRP21-2018-0003). The authors declare no conflict of interest.

Data Availability Statement
The data that support the findings of this study are available from the corresponding author upon reasonable request.
Keywords
charge-to-spin conversions, oxide spintronics, quasi-2D electron gases, spin torque ferromagnetic resonance, STO–AIN interfaces, STO–AIO interfaces

Received: September 30, 2022
Revised: October 31, 2022
Published online: November 24, 2022

[1] A. Ohnomo, H. Y. Hwang, Nature 2004, 427, 423.
[2] K. Han, K. Hu, X. Li, K. Huang, Z. Huang, S. Zeng, D. Qi, C. Ye, J. Yang, H. Xu, A. Ariando, J. Yi, W. Lü, S. Yan, X. Renshaw Wang, Sci. Adv. 2019, 5, eaar7286.
[3] H. Y. Hwang, Y. Iwasa, M. Kawasaki, B. Keimer, N. Nagaosa, Y. Tokura, Nat. Mater. 2012, 17, 103.
[4] Y. Z. Chen, F. Trier, T. Wijnands, R. J. Green, N. Gauquelin, N. Egoavil, D. V. Christensen, G. Koster, M. Hujiben, N. Bovet, S. Macke, F. He, R. Sutarto, N. H. Andersen, J. A. Sulpizio, M. Honig, G. E. D. K. Prawiroatmodjo, T. S. Jespersen, S. Linderoth, S. Ilani, J. Verbeeck, G. Van Tendeloo, G. Rijnders, G. A. Sawatzky, N. Prys, Nat. Mater. 2012, 14, 801.
[5] W. Niu, Y. Can, Y. Zhang, D. V. Christensen, M. V. Soosten, X. Wang, Y. Xu, R. Zhang, N. Prys, Y. Chen, Appl. Phys. Lett. 2017, 111, 021602.
[6] A. D. Caviglia, M. Gabay, S. Gariglio, N. Reyren, C. Cancellieri, J.-M. Triscone, Phys. Rev. Lett. 2010, 104, 126803.
[7] A. Soumyanarayanan, N. Reyren, A. Fert, C. Panagopoulos, Nature 2016, 539, 509.
[8] Z. Zhong, A. Toth, K. Held, Phys. Rev. B 2013, 87, 161102.
[9] A. Manchon, H. C. Koo, J. Nitta, S. M. Frolov, R. A. Duine, Nat. Mater. 2015, 14, 817.
[10] K. Narayanapillai, K. M. Harrison, X. Qiu, A. Annadi, Ariando, T. Venkatesan, H. Yang, Appl. Phys. Lett. 2014, 105, 123105.
[11] H. R. Zhang, Y. Zhang, H. Zhang, J. Zhang, X. Shen, X. Guan, Y. Z. Chen, R. C. Yu, N. Prys, Y. S. Chen, B. G. Shen, J. R. Sun, Phys. Rev. B 2017, 96, 195167.
[12] M. J. Jin, S. Y. Moon, J. Park, V. Modepalli, J. Jo, S. I. Kim, H. C. Koo, B. C. Min, H. W. Lee, S. H. Baek, J. W. Yoo, Nano Lett. 2017, 17, 36.
[13] E. Lesne, Y. Fu, S. Oyarzun, J. C. Rojas Sánchez, D. C. Vaz, H. Naganuma, G. Sicoli, J.-P. Attané, M. Jamet, E. Jacquet, J.-M. George, A. Barthélémy, H. Jaffrès, A. Fert, M. Bibes, L. Vila, Nat. Mater. 2016, 15, 1261.
[14] J.-Y. Chauleau, M. Boselli, S. Gariglio, R. Weil, G. de Loubens, J.-M. Triscone, M. Viret, Europhys. Lett. 2016, 116, 17006.
[15] Y. Wang, R. Ramsawamy, M. Motapothula, K. Narayanapillai, D. Zhu, J. Yu, T. Venkatesan, H. Yang, Nano Lett. 2017, 17, 7659.
[16] Q. Song, H. Zhang, T. Su, W. Yuan, Y. Chen, W. Xing, J. Shi, J. Sun, W. Han, Sci. Adv. 2017, 3, 1602312.
[17] H. Nakayama, T. Yamamoto, H. An, K. Tsuda, Y. Einaga, K. Ando, Sci. Adv. 2018, 4, eaar1899.
[18] J. Zhang, J. Zhang, X. Chi, R. Hao, W. Chen, H. Yang, D. Zhu, Q. Zhang, W. Zhao, H. Zhang, J. Sun, Phys. Rev. B 2022, 105, 195110.
[19] N. Soya, T. Katase, K. Ando, Adv. Mater. 2022, 8, 2200232.
[20] H. Yang, B. Zhang, X. Zhang, X. Yan, W. Cai, Y. Zhao, J. Sun, K. L. Wang, D. Zhu, W. Zhao, Phys. Rev. Appl. 2019, 12, 034004.
[21] L. Liu, C.-F. Bai, Y. Li, H. W. Tseng, D. C. Ralph, R. A. Burhmam, Science 2012, 336, 555.
[22] K. Kondou, R. Yoshimi, A. Tsukazaki, Y. Fukuma, J. Matsuno, K. S. Takahashi, M. Kawasaki, Y. Tokura, Y. Otani, Nat. Phys. 2016, 12, 1027.
[23] A. R. Mellnik, J. S. Lee, A. Richaradda, J. L. Grab, P. J. Mintun, M. H. Fischer, A. Vaezi, A. Manchon, E.-A. Kim, N. Samarth, D. C. Ralph, Nature 2014, 511, 449.
[24] K.-U. Demasius, T. Phung, W. Zhang, B. P. Hughes, S.-H. Yang, A. Kellock, W. Han, A. Pushp, S. S. P. Parkin, Nat. Commun. 2016, 7, 10644.
[25] U. Shashank, R. Medwal, T. Shibata, R. Nongjai, J. V. Vas, M. Duchamp, K. Asokan, R. S. Rawat, H. Asada, S. Gupta, Y. Fukuma, Adv. Quantum Technol. 2021, 4, 2000112.
[26] U. Shashank, R. Medwal, Y. Nakamura, J. R. Mohan, R. Nongjai, A. Kandasami, R. S. Rawat, H. Asada, S. Gupta, Y. Fukuma, Appl. Phys. Lett. 2021, 118, 252406.
[27] P. Noël, F. Trier, L. M. V. Arche, J. Bréhin, D. C. Vaz, G. Garcia, S. Fusil, A. Barthélémy, L. Vila, M. Bibes, J.-P. Attané, Nat. Mater. 2020, 580, 483.
[28] J. Sklenar, W. Zhang, M. B. Jungfleisch, H. Saglam, S. Crudick, W. Jiang, J. E. Pearson, J. B. Ketterson, A. Hoffman, Phys. Rev. B 2017, 95, 224431.
[29] M. Harder, Y. Gui, C.-M. Hu, Phys. Rep. 2016, 661, 1.
[30] R. Medwal, A. Deka, J. V. Vas, M. Duchamp, H. Asada, S. Gupta, Y. Fukuma, R. S. Rawat, Appl. Phys. Lett. 2021, 119, 162403.
[31] A. Deka, B. Rana, R. Anami, K. Miura, H. Takahashi, Y. Otani, Y. Fukuma, Phys. Rev. Res. 2022, 4, 023139.
[32] L. Liu, T. Moriymama, D. C. Ralph, R. A. Burhmam, Phys. Rev. Lett. 2011, 106, 036601.
[33] D. MacNeill, G. M. Stiehl, M. H. D. Guimaraes, R. A. Burham, J. Park, D. C. Ralph, Nat. Phys. 2017, 13, 300.
[34] S. Gupta, R. Medwal, D. Kodama, K. Kondou, Y. Otani, Y. Fukuma, Appl. Phys. Lett. 2017, 110, 022404.
[35] R. Bansal, G. Nirala, A. Kumar, S. Chaudhary, P. K. Muduli, SPIN 2018, 8, 1850018.
[36] Y. Chen, N. Prys, J. E. Kleibeuker, G. Koster, J. Sun, E. Stamatine, B. Shen, G. Rijnders, S. Linderoth, Nano Lett. 2011, 11, 3774.
[37] Z. Q. Liu, C. J. Li, W. M. Lü, X. H. Huang, Z. Huang, S. W. Zeng, X. P. Qi, L. S. Huang, A. Annadi, J. S. Chen, J. M. D. Coey, T. Venkatesan, Ariando, Phys. Rev. X 2013, 3, 021010.
[38] A. Annadi, Q. Zhang, X. Renshaw Wang, N. Tuzla, G. Copinadhan, W. M. Lü, A. R. Barman, Z. Q. Liu, A. Srivastava, S. Saha, Y. L. Zhao, S. W. Zeng, S. Dhar, E. Olsson, B. Gu, S. Yunoki, S. Maekawa, H. Hilgenkamp, T. Venkatesan, Ariando, Nat. Commun. 2013, 4, 1838.