Spin Hall effect investigated by spin Hall magnetoresistance in Pt$_{100-x}$Au$_x$/CoFeB systems

Yoshiaki Saito, Nobuki Tezuka, Shoji Ikeda, Hideo Sato, and Tetsuo Endoh
Spin Hall effect investigated by spin Hall magnetoresistance in Pt$_{100-x}$Au$_x$/CoFeB systems

Yoshiaki Saito, Nobuki Tezuka, Shoji Ikeda, Hideo Sato, and Tetsuo Endoh

AFFILIATIONS
1 Center for Innovative Integrated Electronic Systems, Tohoku University, Sendai 980-0845, Japan
2 Department of Materials Science, Graduate School of Engineering, Tohoku University, Sendai 980-8579, Japan
3 Center for Spintronics Research Network, Tohoku University, Sendai 980-8577, Japan
4 Center for Science and Innovation in Spintronics (Core Research Cluster), Tohoku University, Sendai 980-8577, Japan
5 Research Institute of Electrical Communication, Tohoku University, Sendai 980-8577, Japan
6 Department of Electrical Engineering, Graduate School of Engineering, Tohoku University, Sendai 980-8579, Japan

ABSTRACT

We studied spin Hall effect (SHE) in Pt$_{100-x}$Au$_x$ with various Au compositions $x$ for Pt-Au/CoFeB systems by means of spin Hall magnetoresistance (SMR). We synthesized low resistive, flat, and highly (111)-textured Pt-Au alloy films by sputtering using low pressure Kr gas. We found that spin Hall angle ($\theta_{SH}$), spin Hall conductivity ($\sigma_{SH}$), and spin diffusion length ($\lambda_S$) increase by alloying Pt with Au at certain $x$. The enhancement of $\sigma_{SH}$ is consistent with the theoretically predicted increase in the intrinsic spin Hall conductivity, however quantitatively, there are some discrepancies in $\theta_{SH}$ and $\lambda_S$ between our result and the experimental and theoretical results in the literatures 19 and 20. The discrepancy between our results and previous results would be related to the difference of the nanostructure in Pt-Au alloys related to the scattering from film surfaces and grain boundaries and the degree of phase separation in Pt-Au alloy systems.

I. INTRODUCTION

Current-induced spin-orbit torque (SOT) originating from the spin-Hall effect (SHE) in heavy metal/ferromagnet (HM/FM) systems has attracted attention due to their potential for application in the efficient manipulation of magnetization in nanomagnets for SOT magnetoresistive random access memory (SOT-MRAM), skyrmion and domain wall devices. For their applications, HM with high spin Hall angle ($\theta_{SH}$) and low resistivity $\rho_{xx}$ is necessary for an efficient SOT operation. An engineering to enhance an intrinsic SHE is one of possible schemes to obtain the HM. A recent ab initio electronic structure calculation and rigid band model predict that Pt$_{100-x}$Au$_x$ ($x$ is Au composition) is one of the good candidates for the HM. Actually, a maximum magnitude of $\theta_{SH}$ was observed in Pt$_{50}$Au$_{50}$/NiFe$^{25}$ and Pt$_{75}$Au$_{25}$/Co$^{25}$ systems using ferromagnetic resonance (FMR) and harmonic response, and the maximum magnitude of $\rho_{xx}$ was also observed at the same alloy compositions at $x \sim 50$ and $x \sim 25$, respectively. However, it is not clear why alloy compositions $x$ at which the maximum magnitude of $\theta_{SH}$ was observed are different between Pt-Au/NiFe$^{25}$ and Pt-Au/Co$^{25}$ systems. Moreover, there is a discrepancy in the magnitude of the spin diffusion length ($\lambda_S$) in Pt-Au between Pt-Au/NiFe$^{25}$ and Pt-Au/Co$^{25}$ systems. The value of $\lambda_S$ for Pt$_{75}$Au$_{25}$/Co system is 1.7 nm, whereas $\lambda_S$ in Pt-Au/NiFe is an order of magnitude smaller than that in Pt$_{75}$Au$_{25}$/Co ($\lambda_S \sim 0.2$ nm for Pt$_{50}$Au$_{50}$/NiFe$^{25}$).

Here, we report results of $\theta_{SH}$ and $\lambda_S$ for Pt$_{100-x}$Au$_x$ alloys ($0 \leq x \leq 67$) by investigating the spin hall magnetoresistance (SMR) measurements. The SMR measurement is useful method for determining both magnitudes of $\theta_{SH}$ and $\lambda_S$; therefore, we could accurately evaluate magnitudes of $\theta_{SH}$ and $\lambda_S$ as a function of $x$. We synthesized flat, highly (111)-textured, and low-resistive Pt-Au alloys by sputtering using low-pressure Kr gas. The maximum magnitude of the
resistivity in the prepared Pt$_{100-x}$Au$_x$ alloys ($0 \leq x \leq 67$) is 71.6 $\mu$Omega cm, which is smaller than the previous reported results.\cite{19,20} We discuss the discrepancy of $\theta_{[31]}$ and $\lambda_5$ between the present experiments and the previous theoretical and experimental results\cite{19,20} in terms of the difference in the nanostructure in Pt-Au alloy.

II. EXPERIMENTS

Film stacks, Ta(0.5 nm)/Co$_{20}$Fe$_{60}$B$_{20}$(1.5 nm)/Pt(1.5 ~ 7 nm)/Ta(1.0 nm) and Ta(0.5 nm)/Co$_{20}$Fe$_{60}$B$_{20}$(1.5 nm)/(Pt(0.4 nm)/Au(y nm))$_n$/Ta(1.0 nm) ($y = 0.1, 0.2, 0.4, n$: repetition number), and Ta(0.5 nm)/Co$_{20}$Fe$_{60}$B$_{20}$(1.5 nm)/(Pt(0.2 nm)/Au(y nm))$_n$/Ta(1.0 nm) ($y = 0.4$) were deposited on thermal oxidized Si substrates by rf magnetron sputtering. Base pressure of the sputtering system was less than 3.5 $\times$ 10$^{-7}$ Pa. We prepared devices with various Pt and Pt-Au alloy film thicknesses varied from ~1.5 to ~7.0 nm. For the preparation of the Pt-Au alloys, we artificial synthesized\cite{17,21} Pt-Au alloys; Pt one monolayer and less than one monolayer Au, or Au one monolayer and less than one monolayer Pt were alternately deposited at room temperature. Kr gas pressure ($P_{Kr}$) during deposition of the Pt and Pt-Au is $P_{Kr} = 0.03$ Pa. The easy axis of 1.5 nm thick CoFeB layer lies in in-plane from magnetization measurement using vibrating sample magnetometer (VSM). A dead layer thickness is less than one monolayer (~0.12 nm and ~0.26 nm) for CoFeB/Pt and CoFeB/Pt-Au systems annealed at 300°C, respectively. For all films, the saturation magnetization $M_s$ of Co$_{20}$Fe$_{60}$B$_{20}$ is ~1500 emu/cm$^3$, which is almost the same as that of nominal Co$_{20}$Fe$_{60}$B$_{20}$\cite{22}. The result indicates an absence of a significant magnetic proximity effect.\cite{22} After the deposition, the films were patterned into a microscale Hall bar by photolithography and Ar ion milling. Detailed fabrication process was described in the previous paper.\cite{27} The processed wafers were then annealed at 300°C for an hour. We show the typical device photography and the schematic diagram of the devices in Inset of Fig. 2(c). For the measurements of SMR, the current, which is less than equal to 5 $\mu$A, is passed through the devices in the x-axis direction in Inset of Fig. 2(c) and external magnetic field between -4 and +4 Tesla is applied along either y- and z-axis at 305 K.

III. EXPERIMENTAL RESULTS AND DISCUSSION

Figure 1(a) is the results of x-ray diffraction (XRD) measurements for the stacks with thicknesses of Pt and Pt-Au alloys; $t \sim 7$ nm.

A standard Cu anode x-ray tube was used to generate x-rays. The results show that Pt and Pt-Au alloys have a face-centered-cubic structure with the (111)-texture. The observed satellite peaks in Fig. 1(a) reminiscent the designed multilayer structure. However, the satellite peaks were also observed in Pt monolayer as shown in Fig. 1(a). In addition, assuming the multilayer formation, the artificial thickness period ($\lambda_{\text{multilayers}}$) by using the 20 distance between XRD main peak and 1st satellite peak is estimated to be $\lambda_{\text{multilayers}} \sim 3$ nm, which is much larger than the designed value of $\sim 0.4 \sim 0.8$. The possible reason for observing the satellite peaks could originate from flat and high-quality Pt-Au alloy film. It was reported that satellite peaks were also observed in high-quality flat and epitaxial semiconductor films.\cite{19,20} Therefore, we think the observed satellite peaks and narrow half width at half maximum in XRD patterns indicate the flat and high-quality of the Pt and Pt-Au alloy films prepared. As shown in Fig. 1(a), the peak position of 20 monotonically decreases with increasing $x$ in Pt$_{100-x}$Au$_x$ alloys, indicating that lattice constant of Pt-Au increases with increase of Au composition and artificial synthesized (Pt/Au)$_n$ multilayers form Pt-Au alloys. Therefore, from here, we call (Pt (0.4 nm)/Au (y nm))$_n$ ($y = 0.1, 0.2, 0.4$) and (Pt (0.2 nm)/Au (0.4 nm))$_n$ multilayers Pt$_{100-x}$Au$_x$ ($x = 20, 33, 50, 67$) at. % alloys, respectively. Figures 1(b) and 1(c) show the cross-sectional high-resolution transmission electron microscopy (HR-TEM) images for Ta(0.5 nm)/CoFeB(1.5 nm)/Pt(7 nm)/Ta(1 nm) and Ta(0.5 nm)/CoFeB(1.5 nm)/(Pt$_{0.4}$Au$_{0.6}$)(7 nm)/Ta(1 nm), respectively. Flat and highly (111)-textured Pt and Pt-Au layers were observed. The grain size for both samples is larger than 10 nm.

Figure 2(a) shows the inverse of the device longitudinal resistance ($1/R_{xx}$) multiplied by a geometrical factor ($L/w$), the sheet conductance, $G_{sc} = L/(wR_{xx})$ values are plotted as a function of the HM layer thickness ($t$) for all devices, where $L = 205$ $\mu$m and $w = 5.1$ $\mu$m (Inset of Fig. 2(c)). As shown in Fig. 2(a), there is no anomaly for the devices with Pt-Au alloys, indicating no significant change in resistivity with increase of $t$. On the other hand, there is anomaly at around $t \sim 3.5$ nm for the devices with Pt; the slope significantly increases at thicker thickness region. The result indicates that the resistivity becomes much smaller at thicker $t$ region. In general, grain size increases with increasing $t$, leading to decrease of scattering by grain boundary. The solid line in Fig. 2(b) shows the resistivity of Pt calculated using Eq. (23) from the literature\cite{25} which takes into account scattering by both grain boundaries and film surfaces with...
μ = 229
values p = 1.0 fraction of carriers secularly scattered at the surface of Pt layer, bulk resistivity \( \rho_{\infty} = 9 \, \mu \Omega \text{cm} \), mean free path \( \lambda_{\text{mfp}} = 26 \, \text{nm} \) and the grain boundary penetration parameter \( \xi = 1.34 \), assuming that value of the resistivity (\( \rho_{\text{CoFeB}} \)) for Co\(_{20}\)Fe\(_{60}\)B\(_{20}\) is \( \rho_{\text{CoFeB}} = 229 \, \mu \Omega \text{cm} \) which is the obtained value by the fitting in Fig. 2(a). As shown in Fig. 2(b), the experimental results can be well fitted by the equation, indicating that anomaly in Pt system is related to the scattering from both film surfaces and grain boundaries and scattering due to the grain boundary and surfaces in Pt-Au alloy film is independent on the thickness of the Pt-Au film. The values of \( \rho_{xx} \) for the devices with Pt and Pt\(_{100-x}\)-Au\(_x\) alloys are shown in Fig. 2(c).

Note that \( \rho_{xx} \) in thin thickness region \( t \leq 3.5 \, \text{nm} \) is plotted for the case of Pt. The estimated \( \rho_{xx} \) value has a broad maximum at around \( x \sim 50 \) at which theoretical work also shows the same tendency. However quantitatively, in terms of the absolute values of \( \rho_{xx} \), there is a discrepancy between our result and the theory assuming the disorder calculated by a coherent potential approximation. The theoretically predicted maximum value of \( \rho_{xx} \) for Pt\(_{50}\)Au\(_{50}\) is about 3 times larger than the \( \rho_{xx} \) in Pt. The degree of the increase in \( \rho_{xx} \) is independent on the thickness of the Pt-Au film. The values of \( \rho_{xx} \) for Pt-Au HM electrodes are successfully obtained.

As shown in Fig. 2(b), the experimental results can be well fitted by the equation, indicating that anomaly in Pt system is related to the scattering from both film surfaces and grain boundaries and scattering due to the grain boundary and surfaces in Pt-Au alloy film is independent on the thickness of the Pt-Au film. The values of \( \rho_{xx} \) for the devices with Pt and Pt\(_{100-x}\)-Au\(_x\) alloys are shown in Fig. 2(c).

The largest value of \( \rho_{xx} \) for Pt\(_{50}\)Au\(_{50}\) alloy is about 3 times larger than the \( \rho_{xx} \) in Pt. The degree of the increase in \( \rho_{xx} \) is independent on the thickness of the Pt-Au film. The values of \( \rho_{xx} \) for Pt-Au HM electrodes are successfully obtained.

Figures 3(a) and 3(b) show the typical \( R_{xx} \) versus external magnetic field \( H \) for the devices with Pt\(_{50}\)Au\(_{50}\) and the \( \Delta R_{xx}/R_{xx}^{(0)} \) as a function of \( H \) for the devices with the maximum magnitude of \( \Delta R_{xx}/R_{xx}^{(0)} \) respectively. The magnitude of \( \Delta R_{xx}/R_{xx}^{(0)} \) saturates at around \( |H| = 1.5–2.0 \, \text{T} \), which was consistent with the results of saturation field measured by VSM. As shown in Fig. 3(b), the largest magnitude of \( \Delta R_{xx}/R_{xx}^{(0)} \) is observed for the devices with Pt\(_{50}\)Au\(_{50}\) alloy. Figure 3(c) shows the \( \Delta R_{xx}/R_{xx}^{(0)} \) (average value of \( \Delta R_{xx}/R_{xx}^{(0)} \) at \( H = -2 \, \text{T} \) and \( +2 \, \text{T} \)) as a function of \( t \) for all devices. The largest value of \( \Delta R_{xx}/R_{xx}^{(0)} \) (\( H = 2 \, \text{T} \)) is observed for the devices with Pt\(_{50}\)Au\(_{50}\) alloy. The thickness \( t \) at which the maximum value in of \( \Delta R_{xx}/R_{xx}^{(0)} \) (\( H = 2 \, \text{T} \)) vs \( t \) plot increases with increasing Au composition \( x \), which indicates the increase in \( \lambda_{\xi} \) with increasing \( x \) for Pt\(_{100-x}\)-Au\(_x\) alloys. The solid lines in Fig. 3(c) are the results of fit using the following equations based on the drift diffusion model to the experimental results.

\[
SMR = \frac{\Delta R_{xx}/R_{xx}^{(0)} \sim \theta_{SH}^2}{R_{xx}^{(0)}} \sim \frac{\lambda_{\xi}}{t} \frac{\tanh(t/2\lambda_{\xi})}{1 + \xi} \left[ 1 - \frac{1}{\cosh(t/\lambda_{\xi})} \right],
\]

\[
\xi \equiv \frac{\rho_{\text{Pt-Au\text{CoFeB}}}}{\rho_{\text{CoFeB}} t},
\]

where \( t_{\text{CoFeB}} \) is CoFeB film thickness. The magnitudes of \( \theta_{SH} \) and \( \lambda_{\xi} \) of the Pt-Au HM electrodes are successfully obtained.
Figures 4(a) and 4(b) show the results of the magnitudes of $\theta_{SH}$ and experimentally obtained spin Hall conductivity $\sigma_{SH}$, which is more relevant form to compare the results with the calculated intrinsic spin Hall conductivity for bulk Pt and Pt-Au as a function of $x$ in Pt$_{100-x}$Au$_x$. The magnitude of $\theta_{SH}$ and $\sigma_{SH}$ has a broad maximum at around $x = 20$ and between 0 and 20, respectively. The behavior in the determined $\sigma_{SH}$ shown in Fig. 4(b) is consistent with the reported theoretical and experimental results; however, absolute value and the behavior in the experimentally estimated $\sigma_{SH}$ have large discrepancies between our result and reported results, and between the result in Ref. 19 and Ref. 20. The compositions $x$, and absolute values of $\theta_{SH}$ having the maximum values in $\theta_{SH}$ are $x = 20$ (Pt$_{80}$Au$_{20}$), $x = 50$ (Pt$_{50}$Au$_{50}$) and $x = 25$ (Pt$_{75}$Au$_{25}$), and $+0.11$, about $+0.3$ and $+0.35$ for our result and experimental results in the literatures 19 and 20, respectively. The theory has suggested that SHE in Pt is dominated by the intrinsic band structure effect and the value of $\theta_{SH}$ can be enhanced by alloying Pt with Au by which $\sigma_{SH}$ is not degraded for raising $\rho_{xx}$. The degree of the increase in the experimentally determined $\sigma_{SH}$ for Pt-Au alloys comparing to that for Pt is not so large for all data (our result and literatures 19 and 20). The ratio of the experimentally determined maximum value of $\rho_{xx}$ for Pt-Au alloys to that for Pt: $(\rho_{xx}^{Pt}/\rho_{xx}^{Au})$ is $\rho_{xx}^{Pt}/\rho_{xx}^{Au} = 1.26$ for our result. This indicates that the degree of the increase in the $\theta_{SH}$ for our result is quantitatively consistent with the theoretically predicted relation of $\theta_{SH} \propto \sigma_{SH} \rho_{xx}$. However, the values of $\rho_{xx}$ at $x = 20$ (Pt$_{80}$Au$_{20}$) for our result, $x = 50$ (Pt$_{50}$Au$_{50}$) for literature 19 and $x = 25$ (Pt$_{75}$Au$_{25}$) for literature 20 are $60.9, \sim 100$ and $83 \mu \Omega$cm, respectively, and the difference of maximum $\theta_{SH}$ values between our result and Refs. 19 and 20 could not understand only by the difference in the $\rho_{xx}$ values. The spin scattering would be largely related to not only the increase the $\rho_{xx}$ due to a mixture between Pt and Au but also a nanostructure in Pt-Au layers such as the grain size in Pt-Au. The large grain size of our samples would be one of the reasons for the small values of determined $\theta_{SH}$ compared to those of $\theta_{SH}$ in the literatures 19 and 20. The equilibrium phase diagram of the Pt-Au system suggests that some phase separation might occur in the prepared film in the composition region between Pt$_{15}$Au$_{85}$ and Pt. Therefore, the difference in degree of phase separation in Pt-Au alloy systems might be another possible reason for the difference of $\theta_{SH}$ values.

Figure 4(c) shows the estimated $\lambda_{S}$ as a function of $x$ in Pt$_{100-x}$Au$_x$. The values of $\lambda_{S}$ in Pt-Au alloys are nearly consistent with the previous experimental result in Ref. 20, however, inconsistent with the experimental result in Ref. 19. One order of magnitude smaller $\lambda_{S}$ value observed in Pt-Au alloys reported in Ref. 19 compared with our result and Ref. 20 might be also related to the scattering from film surfaces and grain boundaries and the difference in degree of phase separation in Pt-Au alloy systems. More efforts such as correlation between the nanostructure in HM and the value of $\theta_{SH}$ and $\lambda_{S}$ would be necessary.

IV. CONCLUSIONS

We studied the $\theta_{SH}$ and $\lambda_{S}$ for Pt$_{100-x}$Au$_x$/CoFeB system by using SMR measurements and found that both $\theta_{SH}$ and $\lambda_{S}$ increase by alloying Pt with Au at certain $x$. The quantitative discrepancy between our results in $\theta_{SH}$ and $\lambda_{S}$ and previous results would be related to the difference of the nanostructure in Pt-Au alloys related to the scattering from film surfaces and grain boundaries and the degree of phase separation in Pt-Au alloy systems.

ACKNOWLEDGMENTS

This work was partly supported by the JST-OPERA Program (JPMJP1611) and JSPS KAKENHI (15H05699, 19H00844).

REFERENCES

1. L. Liu, C.-F. Pai, Y. Li, H. W. Tseng, D. C. Ralph, and R. A. Buhrman, Science 336, 555 (2012).
2. 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, I. Tang, Y. Wang, Y. Tserkovnyak, P. K. Amiri, and K. L. Wang, Nat. Nanotechnol. 9, 548 (2014).
3. W. Jiang, P. Upadhyaya, W. Zhang, G. Yu, M. B. Jungfleisch, F. Y. Fradin, J. E. Pearson, Y. Tserkovnyak, K. L. Wang, O. Heinonen, S. G. E. Velthuis, and A. Hofmann, Science 349, 283 (2015).
4. P. P. J. Haazen, E. Mure, J. H. Franken, R. Lavrijsen, Y. H. J. M. Swagten, and B. Koopmans, Nat. Mater. 12, 299 (2013).
5. A. Chernyshov, M. Overby, X. Liu, J. K. Furdyna, Y. Lyandres, J. H. M. Swagten, and B. Koopmans, Nat. Phys. 10, 566 (2009).
6. I. M. Miron, K. Garello, G. Gaudin, P.-J. Zermatten, M. V. Costache, S. Auffret, S. Bandiera, B. Rodmacq, A. Schuhl, and P. Gambardella, Nature 476, 189 (2011).
7. J. Kim, J. Sinha, M. Hayashi, M. Yamanouchi, S. Fukami, T. Suzuki, S. Mitani, and H. Ohno, Nat. Mater. 12, 240 (2013).
S. Fukami, T. Anekawa, C. Zhang, and H. Ohno, Nat. Nanotechnol. 11, 621 (2016).
K.-S. Lee, S.-W. Lee, B.-C. Min, and K.-J. Lee, Appl. Phys. Lett. 104, 072413 (2014).
K. Garello, C. O. Avci, I. M. Miron, M. Baumgartner, A. Ghosh, S. Auffret, O. Boulle, G. Gaudin, and P. Gambardella, Appl. Phys. Lett. 105, 212402 (2014).
C. Zhang, S. Fukami, H. Sato, F. Matsukura, and H. Ohno, Appl. Phys. Lett. 107, 012401 (2015).
M.-H. Nguyen, C.-F. Pai, K. X. Nguyen, D. A. Muller, D. C. Ralph, and R. A. Buhrman, Appl. Phys. Lett. 106, 222402 (2015).
S. Fukami, T. Anekawa, C. Zhang, and H. Ohno, Nat. Nanotechnol. 10, 1038 (2016).
S. V. Aradhya, G. E. Rowlands, J. Oh, D. C. Ralph, and R. A. Buhrman, Nano Lett. 16, 5987 (2016).
M. Baumgartner, K. Garello, J. Mendil, C. O. Avci, E. Grimaldi, C. Murer, I. Feng, M. Gabureac, C. Stamm, Y. Acramann, S. Finizio, S. Wintz, J. Raabe, and P. Gambardella, Nanotechnol. 12, 980 (2017).
Y. Kato, Y. Saito, H. Yoda, T. Inokuchi, S. Shirotori, N. Shimomura, S. Oikawa, A. Tiwari, M. Ishikawa, M. Shimizu, B. Altansargai, H. Sugiyama, K. Koi, Y. Ohsawa, and A. Kurobe, Phys. Rev. Appl. 10, 044011 (2018).
Y. Saito, N. Tezuka, S. Ikeda, H. Sato, and T. Endoh, Appl. Phys. Exp. 12, 053008 (2019).
G. Y. Guo, S. Murakami, T. W. Chen, and N. Nagaosa, Phys. Rev. Lett. 100, 096401 (2008).
M. Obsilbaum, M. Decker, A. K. Greitner, M. Haertinger, T. N. G. Meier, M. Hronský, K. Chodova, S. Wimmer, D. Kôderitzsch, H. Ebert, and C. H. Back, Phys. Rev. Lett. 117, 167204 (2016).
L. Zhu, D. C. Ralph, and R. A. Buhrman, Phys. Rev. Appl. 10, 031001 (2018).
T. Kojima, M. Mizuguchi, T. Koganezawa, K. Osaka, M. Kotsugi, and K. Takanashi, Jpn. J. Appl. Phys. 51, 010204 (2012).
R. M. Bozorth, Ferromagnetism (Wiley-IEEE Press, New York, 1993).
C. L. Canedy, X. W. Li, and G. Xiao, Phys. Rev. B 62, 508 (2000).
K. W. Shin, S. Song, H.-W. Kim, G.-D. Lee, and E. Yoon, Jpn. J. Appl. Phys. 57, 065504 (2018).
P. Fan, K. Yi, J.-D. Shao, and A.-X. Fan, J. Appl. Phys. 95, 2527 (2004).
J. Liu, T. Ohkubo, S. Mitani, K. Hono, and M. Hayashi, Appl. Phys. Lett. 107, 232408 (2015).
J. Kim, P. Sheng, S. Takahashi, S. Mitani, and M. Hayashi, Phys. Rev. Lett. 116, 097201 (2016).
V. P. Amin and M. D. Stiles, Phys. Rev. B 94, 104420 (2016).