Perpendicular Anisotropy and Damping of MBE-grown MgO/Fe/Au(001) and Au/Fe/Au(001) Trilayers

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MgO/Fe/Au(001) and Au/Fe/Au(001) trilayers with Fe layer thickness from 0.4 to 1.2 nm were grown by the molecular beam epitaxy (MBE) method, and the perpendicular magnetic anisotropy (PMA) and magnetization dynamics of the trilayers were studied. The MgO/Fe/Au trilayer exhibited a slightly larger interface anisotropy than the Au/Fe/Au trilayer, and the effective anisotropy of both trilayers decreased with increasing Fe thickness due to the shape anisotropy. The g-factor of both trilayers decreased from the bulk value with decreasing Fe thickness, and MgO/Fe/Au showed a slightly lower g-factor than Au/Fe/Au. The effective damping constant \( \alpha \) of both trilayers increased with decreasing Fe thickness due to the effect of spin pumping, and interestingly the MgO/Fe/Au trilayers showed large damping compared with the Au/Fe/Au ones. These results suggest that the broken inversion symmetry in MgO/Fe/Au leads to a large PMA and damping through Rashba spin-orbit coupling.

Key words: magnetization dynamics, perpendicular anisotropy, Rashba spin-orbit coupling, MgO/Fe/Au

1. Introduction

Perpendicular magnetic anisotropy (PMA) and Gilbert damping are quite important for the efficient writing of the memory cell of spin-transfer-torque magnetic random access memories (STT–MRAM). Recently, insulator / 3d ferromagnet / 5d metal trilayers with broken inversion symmetry along the film normal direction is of great interest, since the broken symmetry is reported to contribute PMA\(^3\) and conversion in-plane current to perpendicular spin current\(^2\) through Rashba spin-orbit coupling. Moreover, PMA of such trilayers is known to be controlled by the application of electric field\(^8,9\), which is quite attractive for voltage-torque magnetization switching\(^7\). The voltage-torque switching is expected to significantly reduce power consumption of MRAM compared to conventional STT–MRAM. In spite of many experimental and theoretical studies of PMA of such trilayers, only few reports on magnetization dynamics\(^8,9\), although the magnetization dynamics is also important for the efficient writing of magnetic materials.

In this report, PMA and magnetization dynamics of MgO/Fe/Au trilayers with broken inversion symmetry were investigated and compared with those of Au/Fe/Au with a symmetric structure in order to discuss the influence of Rashba spin-orbit coupling on the magnetization dynamics. Gilbert damping is known to be proportional to the second-order of spin-orbit interaction\(^10\), however, there has been no report on the relationship between magnetization dynamics and broken inversion symmetry to the extent of our knowledge. Here we report the reduction of g-factor and increase of damping constant \( \alpha \) of symmetry broken MgO/Fe/Au trilayers compared to symmetric Au/Fe/Au trilayers. These results are different from those of MgO/CoFeB/Ta trilayers which exhibit smaller damping constant compared to Ta/CoFeB/Ta due to the suppression of the spin pumping effect at MgO/CoFeB interface\(^8,9\).

2. Experiment

MgO(5) / Fe(\(t_\text{Fe}\)) / Au(20) / Cr(5) / MgO(001) and Au(2) / Fe(\(t_\text{Fe}\)) / Au(20) / Cr(5) / MgO(001) (thickness is in nm) were grown by molecular beam epitaxy (MBE) method in an ultra-high vacuum less than \( 5 \times 10^{-7} \) Pa. The thickness of Fe layer, \( t_\text{Fe} \), was varied from 0.4 nm to 1.2 nm. Prior to the deposition, MgO substrate was cleaned by Ar\(^+\) ion bombardment with an acceleration energy of 1 kV followed by annealing at 1000°C for 2 min. All the layers were deposited at temperature less than 100°C, and Au(20) under layer was annealed at 400°C for 30 min to obtain atomically flat Au surface before the deposition of Fe layer. The deposition rate for all layers was fixed to 0.01 nm/s. Sample structure during the deposition was monitored by reflection high energy electron diffraction (RHEED), and hysteresis loops of the samples were measured by alternating gradient field magnetometer (AGM). Time-resolved magneto-optical Kerr effect (TRMOKE) of the MgO/Fe/Au and Au/Fe/Au trilayers were measured by pump/probe method similarly to our previous works\(^11,12\). Laser beam from an ultra-short pulse fiber laser with a wavelength of 1040 nm, pulse width of 500 fs, a repetition frequency of 100 kHz were split into pump and probe beams, where the probe beam was frequency doubled by a heated lithium borate (LBO) crystal. Typical fluences of the pump and probe beams on the sample were 0.6 mJ/cm\(^2\) and 0.05 mJ/cm\(^2\), respectively. During TRMOKE measurements, an external field \( H_{\text{ext}} \) up to 14 kOe was applied in the direction \( \theta_i = 40–85^\circ \) from the film normal.
3. Results and Discussion

3.1 Film structure

Figure 1 shows RHEED patterns after the deposition of (a), (b) Au(20) under layer, (c), (d) Fe(0.9) layer, (e) MgO(5) upper layer, and (f) Au(2) upper layer, where electron beam was incident along (a), (c), (e), (f) MgO[110] and (b), (d) MgO[110]. As shown in Figs. 1 (a) and (b), atomically flat Au (001) surface with (5 × 1) reconstruction was obtained. The Fe layer was epitaxially grown on Au under layer with a relation Fe(001)[110] // Au(001)[100] as confirmed from RHEED patterns. The Fe layer was epitaxially grown on Au under layer with an epitaxy relationship Fe(001)[110] // Au(001)[100] as confirmed from RHEED patterns in Figs. 1 (a) and (d). Moreover, the streak patterns show layer-by-layer growth of Fe on Au surface. MgO and Au upper layers were also epitaxially grown on Fe layer as shown in Figs. 1 (e) and (f). All samples in this study were confirmed to grow epitaxially on MgO(001) similar to Fig. 1.

Fig. 1 RHEED patterns after deposition of (a), (b) Au(20) under layer, (c), (d) Fe(0.9) layer, (e) MgO(5) upper layer, and (f) Au(2) upper layer. Electron beam was incident parallel to (a), (c), (e), (f) MgO[110] and (b), (d) MgO[110].

3.2 Magnetic anisotropy

Figure 2 shows M–H loops of (a) MgO/Fe/Au and (b) Au/Fe/Au trilayers with various Fe thicknesses. The loops were measured applying a field along the film normal direction, and the magnetization is normalized so that saturation magnetization \( M_s \) equals to unity. Both trilayers exhibited smaller saturation field for thinner Fe thickness, indicating the interface anisotropy becomes competitive for the trilayers with \( t_{Fe} \approx 0.4 \text{ nm} \). By comparing Figs. 2 (a) and (b), MgO/Fe/Au tends to have smaller saturation field than Au/Fe/Au, and obviously MgO/Fe(0.4)/Au exhibited larger PMA than Au/Fe(0.4)/Au. This suggests that PMA was enhanced by the broken inversion symmetry in MgO/Fe/Au trilayers through Rashba spin-orbit coupling\(^{11}\). Larger interface anisotropy of MgO/Fe/Au than Au/Fe/Au was also reported in first-principle calculation\(^{14}\).

Fig. 2 M–H loops along film normal direction of (a) MgO/Fe/Au and (b) Au/Fe/Au trilayers with various Fe thicknesses. Magnetization was normalized so that saturation magnetization \( M_s \) equaled unity.

3.3 Magnetization dynamics

Figure 3 shows typical TRMOKE waveforms of the Au/Fe(0.6)/Au trilayer measured under various external fields \( H_{ext} \) where the field direction was fixed at \( \theta_f = 40^\circ \). In Fig. 3, exponentially decayed background in the raw TRMOKE data was subtracted\(^{12}\). The solid lines in Fig. 3 are fitted curves with the damped oscillation function, \( A \exp(-t/\tau) \sin \omega t \), where \( \tau \) is the relaxation time and \( \omega \) is

Fig. 3 TRMOKE waveforms of Au/Fe(0.6)/Au trilayer measured under various \( H_{ext} \). Direction of \( H_{ext} \) was fixed at \( \theta_f = 40^\circ \) from the film normal. Closed circles and solid lines are experimental and fitting results, respectively.
The solid line in Fig. 4 (a) represents fitting with Eq. (1) where \( \alpha \) is the gyromagnetic constant, and \( \omega \) is the angular frequency of the precession. Figure 4 shows (a) \( H_{\text{ext}} \) dependence of angular frequency \( \omega \) and (b) \( \omega \) dependence of inverse of relaxation time \( 1/\tau \) obtained for Au/Fe(0.6)/Au trilayer. Solid lines in Figs. (a) and (b) represent the fitting with Eq. (1) and Eq. (5), respectively. Dashed lines in Fig. (b) represent four contributions in Eq. (5).

The 1/\( \tau \) dependence of \( H_{\text{ext}} \) is shown in Fig. 4 (b). Gilbert term has a linear dependence on \( \omega \), while TMS term shows a decreasing trend with increasing \( \omega \). The sum of TMS and \( \Delta \theta \) terms tends to move 1/\( \tau \) upward. The TMS term is proportional to \( \Delta H_{\text{eff}}^2 \) as in Appendix, and thus we fit 1/\( \tau \) vs \( \omega \) by varying \( \alpha, \Delta H_{\text{eff}}, \) and \( \Delta \theta \).

Figure 5 shows the dependence of (a) \( H_{\text{ext}} \), (b) \( g \), and (c) \( \alpha \) on the reciprocal Fe layer thickness of MgO/Fe/Au and Au/Fe/Au trilayers. \( \Delta H_{\text{eff}} \) and \( \Delta \theta \) for the fitting were \( \Delta H_{\text{eff}} = 150 \sim 400 \) Oe and \( \Delta \theta = 1.5 \sim 2.5^\circ \), respectively, for all the trilayer. The thickness dependence of \( H_{\text{eff}} \) is expected to follow the equation,

\[
H_{\text{eff}} = \frac{2K_s}{M_s t_F} - \frac{2K_s}{M_s} (6)
\]

where \( K_s \) is the surface anisotropy of both interfaces and

\[
E = -M_s H_{\text{ext}} \cos(\theta_H - \theta) + \frac{M_s H_{\text{eff}}}{2} \sin^2 \theta
\]

The solid line in Fig. 4 (a) represents fitting with Eq. (1) to evaluate \( H_{\text{eff}} \) and \( g \) of Au/Fe(0.6)/Au trilayer. The dependence of 1/\( \tau \) on \( \omega \) was fitted with the following expression taking into account Gilbert damping \( \alpha \), anisotropy distribution \( \Delta H_{\text{eff}} \), anisotropy axis distribution \( \Delta \theta \), and two-magnon scattering (TMS)\(^{18-20}\).

\[
\frac{1}{\tau} = \frac{\alpha}{T_{\text{Gilbert}}} + \frac{1}{T_{\text{TMS}}} + \frac{\Delta H_{\text{eff}}}{\gamma} + \frac{\Delta \theta}{\gamma}
\]

where the angular frequency of the precession. Figure 4 shows (a) \( H_{\text{ext}} \) dependence of angular frequency \( \omega \) and (b) \( \omega \) dependence of inverse of relaxation time \( 1/\tau \). The following analytical expressions were used to fit the \( H_{\text{ext}} \) dependence of \( \omega \).

\[
\omega = \gamma \sqrt{H_{\theta \theta} H_{\phi \phi}}
\]

\[
H_{\theta \theta} = H_{\text{ext}} \cos(\theta_H - \theta) + H_{\text{eff}} \cos^2 \theta
\]

\[
H_{\phi \phi} = H_{\text{ext}} \cos(\theta_H - \theta) + H_{\text{eff}} \sin \theta \sin \theta
\]

\[
\frac{1}{\tau} = \frac{1}{\gamma_{\text{Gilbert}}} + \frac{1}{\gamma_{\text{TMS}}} + \frac{1}{\gamma_{\text{H_{\text{eff}}}}} + \frac{1}{\gamma_{\text{\Delta \theta}}}
\]

\[
= \frac{\alpha}{2} (H_{\theta \theta} + H_{\phi \phi}) + \frac{1}{2} \frac{\partial \omega}{\partial \theta_H} \Delta \theta_H
\]
$K_c$ is volume anisotropy consisting of crystalline and shape anisotropies. From Fig. 5 (a), $K_c$ is estimated to be around $-1.6 \times 10^5$ erg/cc for both trilayers, which is roughly consistent with the shape anisotropy, $2\pi M_s^2 = 1.8 \times 10^5$ erg/cc. Large slope was confirmed for MgO/Fe/Au compared to Au/Fe/Au, and $K_c = 0.69 \pm 0.05$ mJ/cm² for MgO/Fe/Au and $K_c = 0.58 \pm 0.07$ mJ/cm² for Au/Fe/Au, which agrees with the discussion in Fig. 2. The g-factor of both trilayers decreased from $-2.05$ to $-1.95$ with decreasing the thickness, and approaches to $2.07$ when the thickness of Fe is infinitely thick, which is roughly consistent with the bulk value ($g = 2.09^{21}$). The decrease of g-factor with decreasing the Fe thickness is expected in the presence of the interfacial anisotropy.$^{20,23}$ MgO/Fe/Au trilayers seem to have slightly lower g-factor, which may be related to Rashba spin-orbit coupling in symmetry broken MgO/Fe/Au trilayers. However, there exists the difference of g-factor between MgO/Fe/Au and Au/Fe/Au even when the thickness of Fe is infinitely thick, and thus we are not sure that the difference is significant.

The damping constants of both trilayers increased with decreasing the Fe thickness as shown in Fig. 5 (c), and approached to $\alpha = 0.001$ at $1/t_2 = 0$. The intrinsic Gilbert damping $\alpha_{intrinsic}$ is reported to be $0.0025$ for Fe, and to reduce to $0.0005$ for Fe$_{75}$Co$_{25}$ due to the shift of Fermi energy.$^{24}$ These values roughly agree with the present extrapolated $\alpha$ by considering the error bar of the extrapolation of $\approx 0.001$. The increasing trend of $\alpha$ with decreasing $t_F$ is due to the effect of spin pumping into Au layer. The enhanced damping due to the spin pumping is expressed by using effective spin mixing conductance $g_{eff}$ as,

$$\Delta \alpha_{sp} = g_{sp} \frac{g_{eff}}{4\pi M_s} \frac{1}{g_{Fe}},$$

where $g_{sp}$ is the Bohr magneton.$^{25,26}$ Spin diffusion lengths of Au and Cr are reported to be $\lambda_{Au} = 35$ nm$^{27}$ and $\lambda_{Cr} = 4.5$ nm$^{28}$, respectively, which suggests that injected spin current into Au/Fe under layer will be fully absorbed. Thus the $g_{eff}$ of Au/Fe/Au trilayer is given by,

$$g_{eff} = g_{Au}^{1+} + g_{Au}^{1-} \left(1 - e^{-2\lambda_{Au}/\lambda_{Au}}\right),$$

where $g_{Au}^{1+}$ is the spin mixing conductance at Fe/Au interface, and $t_{Au}$ is upper Au thickness.$^{29}$ The 2nd term in Eq. (8) represents the spin pumping into upper Au layer. The slope of $g_{eff}$ of Au/Fe/Au trilayers was estimated at $0.0055 \pm 0.0004$ nm$^{-1}$ from Fig. 5 (c), which gives $g_{Au}^{1+} = 5.8 \times 10^{14}$ cm$^{-2}$, where g-factor is approached to 2. The estimated $g_{Au}^{1+}$ is comparable to the theoretical value$^{20}$ of $g_{eff}^{1+} = 1.2 \times 10^{15}$ cm$^{-2}$. Based on Eq. (8), the effective spin mixing conductance $g_{eff}$ of MgO/Fe/Au trilayers equals to $g_{eff}^{1+}$, because no spin current flows into insulating MgO layer. Thus the slope of $\alpha$ of MgO/Fe/Au trilayer is expected to be $0.0055$ nm$^{-1}$ (roughly 10% smaller than that of Au/Fe/Au trilayer, since the 2nd term of Eq. (8) disappears). However, the slope of $\alpha$ of MgO/Fe/Au trilayer is estimated to be $0.0062 \pm 0.0007$ nm$^{-1}$ from Fig. 5 (c), indicating an additional interface contribution to the damping. Kambersky pointed out the damping constant is influenced by spin-orbit coupling and density of state at the Fermi level.$^{10,30}$ As discussed in Fig. 2, larger PMA in MgO/Fe/Au than Au/Fe/Au may be related to Rashba spin-orbit coupling originated from broken inversion symmetry in MgO/Fe/Au, and Rashba spin-orbit coupling may also be responsible for the increase of the damping of MgO/Fe/Au. The reduction of the bandwidth of Fe is expected when insulating MgO is placed adjacent to Fe, which modifies the density of states.

4. Conclusion

The contribution of two-magnon scattering $1/|TMS|$ in Eq. (5) is calculated as$^{10,20}$

$$\frac{1}{|TMS|} = N_0 \int \frac{C(k)}{\omega} \frac{\text{Im} \left( \frac{1}{\omega_k - \omega + i\delta\omega_k} \right) d\omega_k}{|k|},$$

where $k$ is the magnon wave vector, and $\kappa$ is its amplitude. $N_0$, $C(k)$, $\omega_k$, and $\delta\omega_k$ are the scattering intensity, the correlation function, the spin wave dispersion, and the inverse lifetime of the spin wave, respectively, and these are expressed as$^{17,18}$

$$N_0 = \gamma^4 \left( 4H_{\phi0}^2 \cos^2 \theta + 4H_{\phi0}^2 \cos^2 2\theta - 8H_{\phi0} H_{\phi0} \cos \theta \cos 2\theta \right) \Delta H_{\phi0}^2,$$

$$C(k) = \frac{2\pi \xi^2}{(1 + (k\xi)^2)^{3/2}},$$

$$\omega_k = \gamma \sqrt{H_{\phi0}(k)H_{\phi0}(k)},$$

$$\delta\omega_k = \alpha (H_{\phi0}(k) + H_{\phi0}(k)),$$
where $\zeta$ is the correlation length. $H_{00}(k)$ and $H_{0\theta}(k)$ are given by\(^{17}\),

\[
H_{00}(k) = H_{000} + \frac{M_s}{\mu_0} (1 - N_k) \cos^2 \phi_k + \frac{2A_{ex}}{M_s} k^2,
\]

(A6a)

\[
H_{0\theta}(k) = H_{0\theta 0} + \frac{M_s}{\mu_0} (1 - N_k) \times \left\{ -\sin^2 \theta + \cos^2 \theta \sin^2 \phi_k \right\} + \frac{2A_{ex}}{M_s} k^2,
\]

(A6b)

where $\mu_0$ is the permeability of vacuum, $A_s$ the exchange stiffness, and $\phi_k$ the azimuth angle of the spin wave. The wave number dependent demagnetizing factor $N_k$ is given by\(^{17}\),

\[
N_k = \frac{1}{k t_{Fe}}.
\]

(A7)

Here we set $A_s = 20 \text{ pJ/m}$, $\xi = 2 \text{ nm}$, and $M_s = 1700 \text{ emu/cc}$, respectively to obtain the dashed line of the two-magnon contribution $1/T_{\text{MS}}$ shown in Fig. 4 (b).

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References

1) S. E. Barnes, J. Ieda, and S. Maekawa: \textit{Sci. Rep.}, 4, 4105 (2014).
2) I. M. Miron, G. Gaudin, S. Auffret, B. Rodmacq, A. Schuhl, S. Pizzini, J. Vogel, and P. Gambardella: \textit{Nat. Mater.}, 9, 230 (2010).
3) T. Maruyama, Y. Shiota, T. Nozaki, K. Ohta, N. Toda, M. Mizuguchi, A. A. Tulapurkar, T. Shinjo, M. Shiraiishi, S. Mizukami, Y. Ando, and Y. Suzuki: \textit{Nat. Nanotech.}, 4, 158 (2009).
4) Y. Shiota, S. Murakami, F. Bonell, T. Nozaki, T. Shinjo, and Y. Suzuki: \textit{Appl. Phys. Express.}, 4, 043005 (2011).
5) M. Tsujikawa, S. Haraguchi, T. Oda, Y. Miura, and M. Shirai: \textit{J. Appl. Phys.}, 109, 07C107 (2011).
6) X. W. Guan, X. M. Cheng, T. Huang, S. Wang, K. H. Xue, and X. S. Miao: \textit{J. Appl. Phys.}, 119, 133905 (2016).
7) Y. Shiota, T. Nozaki, F. Bonell, S. Murakami, T. Shinjo, and Y. Suzuki: \textit{Nat. Mater.}, 11, 39 (2012).
8) S. Iihama, S. Mizukami, H. Naganuma, M. Oogane, Y. Ando, and T. Miyazaki: \textit{Phys. Rev. B}, 89, 174416 (2014).
9) A. Okada, S. He, B. Gu, S. Kanai, A. Soumyanarayanan, S. T. Lim, M. Tran, M. Mori, S. Maekawa, F. Matsukura, H. Ohno, and C. Panagopoulos: \textit{Proc. Natl. Acad. Sci. USA}, 114, 3815 (2017).
10) V. Kambersky: \textit{Czech. J. Phys. B}, 26, 1366 (1976).
11) T. Kato, K. Nakazawa, R. Komiya, N. Nishizawa, S. Tsunashima, and S. Iwata: \textit{IEEE Trans. Magn.}, 44, 3380 (2008).
12) T. Kato, Y. Matsumoto, S. Okamoto, N. Kituchi, O. Kitakami, N. Nishizawa, S. Tsunashima, and S. Iwata: \textit{IEEE Trans. Magn.}, 47, 3036 (2011).
13) T. Kato, Y. Matsumoto, S. Kashima, S. Okamoto, N. Kituchi, S. Iwata, O. Kitakami, and S. Tsunashima: \textit{IEEE Trans. Magn.}, 48, 3288 (2011).
14) M. Tsujikawa, S. Haraguchi, and T. Oda: \textit{J. Appl. Phys.}, 111, 083910 (2012).
15) H. Shull: \textit{Phys. Rev.}, 97, 555 (1955).
16) J. -M. Beaujour, D. Ravelosona, I. Tudosa, E. E. Fullerton, and A. D. Kent: \textit{Phys. Rev. B}, 80, 184415 (2009).
17) R. D. MeMichael and P. Krivosik: \textit{IEEE Trans. Magn.}, 40, 2 (2004).
18) P. Landeros, R. E. Arias, and D. L. Mills: \textit{Phys. Rev. B}, 77, 214405 (2008).
19) S. Iihama, A. Sakuma, H. Naganuma, M. Oogane, S. Mizukami, and Y. Ando: \textit{Phys. Rev. B}, 94, 174425 (2016).
20) T. Kato, D. Oshima, and S. Iwata, \textit{Crystals}, 9, 27 (2019).
21) A. J. P. Meyer, G. Asch: \textit{J. Appl. Phys.}, 32, 3305 (1961).
22) J. M. Shaw, H. T. Nembach, and T. J. Silva: \textit{Phys. Rev. B}, 87, 054416 (2013).
23) J. M. Shaw, H. T. Nembach, T. J. Silva, and C. T. Boone: \textit{J. Appl. Phys.}, 114, 243906 (2013).
24) M. A. W. Schoen, D. Thonig, M. L. Schneider, T. J. Silva, H. T. Nembach, O. Eriksson, O. Karis, and J. M. Shaw: \textit{Nat. Phys.}, 12, 839 (2016).
25) J. Foros, G. Woltersdorf, B. Heinrich, and A. Brataas: \textit{J. Appl. Phys.}, 97, 10A714 (2005).
26) J. M. Shaw, H. T. Nembach, and T. J. Silva: \textit{Phys. Rev. B}, 85, 054412 (2012).
27) H. Kurt, W. -C. Chiang, C. Richt, K. Eid, W. P. Pratt Jr., and J. Bass: \textit{J. Appl. Phys.}, 93, 7918 (2003).
28) A. Zambano, K. Eid, R. Loloee, W. P. Pratt Jr., and J. Bass: \textit{J. Magn. Magn. Mat.}, 253, 51 (2002).
29) M. Zwierzycki, Y. Tserkovnyak, P. J. Kelly, A. Brataas, and G. E. W. Bauer: \textit{Phys. Rev. B}, 71, 064420 (2005).
30) V. Kambersky: \textit{Phys. Rev. B}, 76, 134416 (2007).

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