Current control of magnetic anisotropy via stress in a ferromagnetic metal waveguide

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(Received 27 December 2015; revised manuscript received 2 March 2016; published 11 April 2016)

We demonstrate that in-plane charge current can effectively control the spin precession resonance in an Al$_2$O$_3$/CoFeB/Ta heterostructure. Brillouin light scattering was used to detect the ferromagnetic resonance field under microwave excitation of spin waves at fixed frequencies. The current control of spin precession resonance originates from modification of the in-plane uniaxial magnetic anisotropy field $H_k$, which changes symmetrically with respect to the current direction. Numerical simulation suggests that the anisotropic stress introduced by joule heating plays an important role in controlling $H_k$. These results provide new insight into current manipulation of magnetic properties and have broad implications for spintronic devices.

DOI: 10.1103/PhysRevB.93.140404

Introduction. Magnetic anisotropy plays an important role in the performance of high-density spintronic devices including spin valves [1,2], magnetic tunnel junctions [3–6], and emerging multiferroic technologies [7]. Such anisotropy defines the low-energy orientation of the magnetization as well as the stability of the magnetization with respect to external fields, electric currents [8], and temperature-induced fluctuations [9,10]. The control of magnetic anisotropy is typically realized by controlling the growth condition of the magnetic layer [11], switching substrates [12], applying external stress [13], heating [11], or an external electric field [14]. Recently, perpendicular magnetic anisotropy has been achieved in oxide/ferromagnetic metal heterostructures, such as MgO/CoFeB, leading to low critical currents for spin transfer torque switching of tunnel junctions [6]. Therefore, approaches to effectively control magnetic anisotropy as well as elucidating their physical origins become important for further development of multifunctional spintronic devices.

Charge current has recently been utilized to manipulate magnetization including control of magnetic domain-wall motions and magnetization switching [3,15–19]. Efficient control can be achieved using spin-orbit torques (SOTs) originating from either the spin Hall effect in the bulk of a heavy metal [20] or the Rashba effect at a magnetic interface [21]. CoFeB-based alloys have attracted great attention due to their high magnetoresistance [22] and they are commonly used as the electrode material for magnetic tunnel junctions. Although charge-current-induced magnetization manipulation of CoFeB has been extensively studied, current-induced magnetoelastic effects have been rarely discussed, even though CoFeB is known to exhibit a large magnetoelectric constant [23].

In this Rapid Communication, we investigate current-induced magnetic resonance shifts in a CoFeB/Ta waveguide deposited on an Al$_2$O$_3$ substrate with the Brillouin light scattering (BLS) technique. The magnetic resonance shift exhibits both symmetric and asymmetric dependences when the direction of the direct current (dc) is reversed. A number of mechanisms which can contribute to the asymmetric shift have been investigated previously [21,24], including the Oersted field, the spin Hall effect, and the Rashba effect. In this Rapid Communication, we focus on the symmetric frequency shift, which can be understood as arising from a current-induced change in the in-plane uniaxial magnetic anisotropy field $H_k$. A modification of $H_k$ up to ~24% is realized using a moderate current density of $4 \times 10^{6}$ A/cm$^2$. Numerical simulations suggest that the current-controlled magnetic anisotropy originates at least in part from anisotropic stress in the waveguide, generated by joule heating from the in-plane current flow. Our study shows that the effective $H$ field induced by anisotropic stress can play an important role in magnetization control in addition to the frequently discussed fieldlike SOT from the spin Hall effect or interfacial Rashba torque in a CoFeB/Ta bilayer structure [25].

Sample structure and characterization with the magneto-optical Kerr effect. The samples investigated are a series of Co$_{40}$Fe$_{40}$B$_{20}$(10)/Ta(10) films deposited onto an Al$_2$O$_3$ substrate by sputtering [20] where the numbers in parentheses represent the layer thicknesses measured in nanometers. Following deposition, the bilayer structure was patterned into a 10-μm-wide and 200-μm-long waveguide. After the deposition of a 240-μm-thick SiO$_2$ insulating layer, a 5-μm-wide Cu(150)/Au(10) antenna was created on top of the bilayer waveguide as depicted in Fig. 1(a). From the measured resistance of the bilayer structure 193 Ω, the resistivity of the bilayer structure of 193 μΩ cm was calculated. These bilayer structures have been previously used to investigate magnetic switching [20] and spin-wave amplification via SOTs [26]. Whereas phenomena driven by SOTs were observed in this sample, it does not appear to be the most critical mechanism behind the experimental observation of resonance field shifts discussed in this Rapid Communication.

We first characterize the CoFeB samples with magneto-optical Kerr effect (MOKE) measurements at room temperature as presented in Figs. 1(b) and 1(c). A laser beam diameter of ~2.5 μm was placed in the center of the bilayer waveguide in all MOKE measurements. Due to the strong demagnetization field, the magnetization lies on the x-y plane,
the spin waves propagating along the CoFeB waveguide with the in-plane magnetic anisotropy is indeed uniaxial in the ter. The Fig. 1(d) inset shows a typical BLS raw spectrum from Sandercock-type multipass tandem Fabry-Pérot interferometer of the backscattered light was collected and sent to a linearly polarized laser beam was normally incident on A linearly polarized laser beam was normally incident on were excited by a microwave current through the antenna. frequency domain under microwave excitation at a fixed frequency. BLS intensity as a function of external field magnetic-field directions. (c) Polar plot of the normalized remanent BLS experiment. (b) Measured MOKE data with three different current passing through the waveguide. Hence, there must exist other mechanisms that overcome the increase in $H_R$ due to the decrease in $4\pi M_{eff}$ by simple heating and reduce $H_R$ at higher dcs.

To further investigate the origin of the symmetric reduction of $H_R$ with respect to the dc. Joule heating is known to cause a reduction of $4\pi M_{eff}$ and hence a symmetric shift in $H_R$. We examine the effect of simple heating by raising the sample temperature uniformly on a heater stage. As shown in Fig. 2(b), $H_R$ is observed to shift upward at a higher temperature, which is opposite to the change in $H_R$ observed in our experiments by passing dcs through the waveguide. Hence, there must exist other mechanisms that overcome the increase in $H_R$ due to the decrease in $4\pi M_{eff}$ by simple heating and reduce $H_R$ at higher dcs.

To begin, we study how the spin-wave intensity, proportional to the integrated BLS intensity, changes with the applied magnetic field at zero dc. The spin wave excited by a fixed microwave frequency exhibits a resonance behavior as shown in Fig. 1(d). The resonance can be well fitted with a squared Lorentzian function from which the peak position $H = H_R$ or the field corresponding to the maximal BLS intensity can be extracted. The resonance field and the frequency of uniform precession can be related by the Smit-Suhl equation [29] (see the Supplemental Material [30]),

$$f = \frac{\gamma}{2\pi} \sqrt{(H_R - H_k)(H_R + 4\pi M_{eff})},$$

where $\gamma$ is the gyromagnetic ratio and $4\pi M_{eff}$ is the effective demagnetization field which also includes the out-of-plane anisotropy field. Strictly speaking, our BLS experiments measure spin waves with small but finite wave vectors instead of the spatially uniform precession. This would lead to a constant offset of $H_R$ by $\sim 3\%$ from the peak in BLS-resonance curve as demonstrated by our previous work on CoFeB/Ta on Si substrates [26]. Because this offset is small, we will approximately equate $H_R$ with the field corresponding to the peak in the BLS spectra as shown in Fig. 1(d).

We then investigate how the resonant magnetic field $H_R$ changes as a dc passes through the waveguide. Our key finding is that $H_R$ decreases with increasing dc as shown in Fig. 2(a) at $f = 8\, \text{GHz}$. The change in $H_R$ exhibits both symmetric and antisymmetric behaviors with respect to the dc. The antisymmetric component can be attributed to a combination of Oersted field, spin Hall effect, and Rashba effect [21,24]. The induced magnetic field from these effects lies along the direction of the external magnetic field, and the direction of the effective field is reversed by reversing the dc direction, leading to an antisymmetric change in $H_R$ with dc.

We focus here on the symmetric reduction of $H_R$ with respect to the dc. Joule heating is known to cause a reduction of $4\pi M_{eff}$ and hence a symmetric shift in $H_R$. We examine the effect of simple heating by raising the sample temperature uniformly on a heater stage. As shown in Fig. 2(b), $H_R$ is observed to shift upward at a higher temperature, which is opposite to the change in $H_R$ observed in our experiments by passing dcs through the waveguide. Hence, there must exist other mechanisms that overcome the increase in $H_R$ due to the decrease in $4\pi M_{eff}$ by simple heating and reduce $H_R$ at higher dcs.

To further investigate the origin of the symmetric reduction of $H_R$, H-field-dependent measurements were performed under different excitation microwave frequencies. The maximal symmetric shift defined by $\Delta H_{symm} \equiv \frac{1}{2}(H_R(1) - H_R(-1))$ - $H_R(1 = 0)$ is plotted as a function of $H_R(1 = 0)$ at each microwave frequency in Fig. 2(c) with a linear fitting line. In other words, $\Delta H_{symm}$ represents the symmetric shift in the resonant field $H_R$ at the highest current ($I_{max} = 8\, \text{mA}$) applied in our experiments. To understand
correlation between $\Delta H_{\text{symm}}^m$ and $H_R (I = 0)$, we modify the uniform frequency formula (2) to take into account the dc effect phenomenologically as the following:

$$f = \frac{\gamma}{2\pi} \sqrt{\frac{(H_R - H_R,0 + C_1I^2)}{4\pi M_{\text{eff},0} + C_1I^2}}. \tag{3}$$

Here we only keep the lowest-order even contribution from the dc, i.e., the term proportional to $I^2$. $H_R,0$ and $4\pi M_{\text{eff},0}$ are the uniaxial anisotropy field and the effective magnetization without dc. The symmetric dependences of $M_{\text{eff}}$ and $H_R$ with respect to dc are explicitly written by introducing $C_1I^2$ and $C_2I^2$. With changing dc, $H_R$ is shifted, but $f$ remains the same because of the fixed frequency of the microwave excitation. By taking the derivative with respect to $I^2$, we can obtain the desired relationship between $\Delta H_{\text{symm}}^m$ and $H_R (I = 0)$ (see the Supplemental Material [30]),

$$\Delta H_{\text{symm}}^m = A_1 H_R (I = 0) + A_2,$$

where

$$A_1 \equiv -\frac{(C_2-C_1)I_{\text{max}}^2}{4\pi M_{\text{eff},0}},$$

$$A_2 \equiv C_1 I_{\text{max}}^2 - A_1 (H_R,0 - C_1I_{\text{max}}^2). \tag{4}$$

Thus, $A_1$ and $A_2$ correspond to the slope and y intercept of the fitting line and are determined to be 0.014 ± 0.001 and −9.9 ± 0.5 Oe, respectively. Using these values, we determine $C_1 I_{\text{max}}^2 = 9.4 \pm 0.5$ Oe and $C_2 I_{\text{max}}^2 = (-0.014 \pm 0.001)4\pi M_{\text{eff}}|_{I=0} + 9.4$ Oe. We interpret the $C_2$ term as the reduction of $4\pi M_{\text{eff}}$ caused by joule heating. Based on Bloch’s law [31], an ~1.4% reduction of $4\pi M_{\text{eff}}$ corresponds to a temperature rise of 22 K. The $C_1$ term can be interpreted as the change in $H_R$, which decreases by about 24% at $I = I_{\text{max}}$. Based on the $C_1$ and $C_2$ values, we plot $H_R$ as a function of dc using $H_R = H_R,0 - C_1I^2$ as shown in Fig. 2(d).

Simulation results. Next, we explore the possibility that the anisotropic stress, induced by joule heating from current flow through the bilayer waveguide, plays an important role in the modification of $H_R$. We used the thermal stress module of COMSOL software (see Supplemental Material [30]). We took the power dissipation through the waveguide as a heat source and calculated spatial profiles of stresses. Figure 3 shows that the calculated stress values for the waveguide along the $x(\sigma_x)$ and $y(\sigma_y)$ directions at $I = 8$ mA. The stress values are negative, indicating that the larger thermal expansion of CoFeB/Ta compared to the Al$_2$O$_3$ substrate leads to compressive stresses on CoFeB. The anisotropic stresses arise mainly due to the stripelike shape of the waveguide as the stress difference between the two axes becomes zero if the waveguide has a square rather than a rectangular geometry. Based on the volume averaged stress values, we calculated the magnetoelastic energy $E_\sigma$ given by [27]

$$E_\sigma = \frac{1}{2} \lambda (\sigma_x \sin^2 \phi + \sigma_y \cos^2 \phi), \tag{5}$$

where $\lambda$ is the magnetoelastic constant of CoFeB, $20 \times 10^{-6}$ [23], $\phi$ is the angle between the $x$ axis and the magnetization as shown in Fig. 1(a). The effective magnetic field associated with $E_\sigma$ can change the uniform frequency formula. By adding the stress induced energy $E_\sigma$ to the total magnetic free energy $E$ and using the Smit-Suhl formula [29] (see the Supplemental Material [30]), we obtain the modified uniform frequency formula given by

$$f = \frac{\gamma}{2\pi} \sqrt{\frac{(H_R - [H_R - \frac{\lambda}{2\mu}(\sigma_x - \sigma_y)])}{4\pi M_{\text{eff}}}}. \tag{6}$$

with the calculated stress difference $\sigma_x - \sigma_y = 1.6 \times 10^6$ dyn/cm$^2$ and $M_s = 1273 \pm 80$ emu/cm$^3$ [23], we obtain a stress-induced field of 7.5 ± 0.5 Oe, which is reasonably close to the measured $H_R$ decrease of 9.5 Oe at $I = \pm 8$ mA.
To further confirm that anisotropic stress plays a key role in the observed magnetic resonance shift with dcs, we compare the observed symmetric change in the resonance field defined by

$$\Delta H_{\text{symm}} \equiv \frac{H_r(I) + H_r(-I)}{2} - H_r(0)$$

(7)

for two different substrates Al$_2$O$_3$ and Si/SiO$_2$. The data for Al$_2$O$_3$/CoFeB(10)/Ta(10) and Si/SiO$_2$(500)/CoFeB(10)/Ta(10) are shown in Fig. 4. The CoFeB waveguide on the Si substrate was 8-µm wide and 270-µm long. $\Delta H_{\text{symm}}$ for CoFeB on the Si substrate increases with dcs, which is consistent with a simple joule heating effect whereas that of CoFeB on the Al$_2$O$_3$ substrate decreases with dcs.

A similar COMSOL calculation was performed for the Si/SiO$_2$/CoFeB(10)/Ta(10) structure. The calculated stress difference $\sigma_y - \sigma_x$ was only $2.0 \times 10^7$ dyn/cm$^2$. Since $E_\sigma$ depends on the difference in stresses, this leads to a much smaller $\Delta H_{\text{symm}}$ compared to the one on the Al$_2$O$_3$ substrate. This small difference between $\sigma_x$ and $\sigma_y$ originates from the fact that SiO$_2$ has a small thermal expansion coefficient ($0.6 \times 10^{-5}$) compared to that of Al$_2$O$_3$ ($7.5 \times 10^{-5}$). Thus, the stress from the anisotropic thermal expansion of CoFeB on the Si substrate is limited, and the isotropic thermal stress dominates (see the Supplemental Material [30]). Previous measurements of magnetoelasticity for CoFeB films grown on flexible substrates proved that stress can lead to changes in magnetic anisotropy, and these results qualitatively agree with our observations [32,33].

**Conclusion.** We have investigated the uniaxial magnetic anisotropy field of a CoFeB/Ta waveguide on an Al$_2$O$_3$ substrate and its dependence on an in-plane charge current with the BLS technique. The in-plane uniaxial magnetic anisotropy field is modified by $\sim 24\%$ at a modest charge current density of $4 \times 10^6$ A/cm$^2$. The modification of $H_k$ is symmetric with respect to the current direction, which cannot be explained by either the spin Hall or the Rashba effect. Our simulations suggest that anisotropic stress induced by joule heating from dcs passing the waveguide can cause a change in $H_k$, which agrees reasonably well with the experimental observation. This joule-heating-induced anisotropic stress control of magnetic anisotropy may offer additional design flexibility in the development of new spintronic devices, such as spin valves and magnetic tunneling junctions.

**Acknowledgments.** K.A., X.M., K.S.O., and X.L. were supported by SHINES, an Energy Frontier Research Center funded by the U.S. Department of Energy (DoE), Office of Science, Basic Energy Science (BES) under Award No. DE-SC0012670. J.Y. and J.E. were supported by NSF DMR-1206404. The work at Cornell was supported by the NSF/MRSEC Program (Program No. DMR-1120296) through the Cornell Center for Materials Research.

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