Spin wave (SW) as fundamental dynamic magnetic excitations in ferromagnets and ferrites has been studied for more than five decades due to its potentials in ultrahigh density memories, ultrahigh frequency inductors, tunable filters, and spin wave logic devices. A large number of experimental observations and theoretical considerations have been well expounded. Among these experimental studies, several measuring techniques have been developed to study the excitation and propagation of spin waves, such as ferromagnetic resonance (FMR), Brillouin light scattering (BLS), time-resolved magneto-optics, inductive technique, and propagating spin wave spectroscopy (PSWS). The principle of PSWS measurements is to produce a non-uniform microwave field so that it couples to spin waves with nonzero wave vectors. This is realized by sending microwave current through a microwave antenna. PSWS technique is well established for studying spin waves in yttrium iron garnet insulating films and recently has been used for the study of metallic materials.

In recent years, electric field modulation of spin waves has also attracted much attention due to its potential in spin wave devices. Electric modulation of spin waves in ferroelectric/ferromagnetic heterostructures has attracted much attention due to its potential in spin wave devices. In this letter, we report our work on quantitating the electric field induced modulation of spin wave frequency and anisotropy field in CoFeB/(011) PMN-PT structure by propagating spin wave spectroscopy (PSWS) technique. To verify the reliability of PSWS measurements, magneto-optical Kerr effect measurement is also performed, the result of which is comparable with that from the PSWS measurement.

Spin wave theory has been well established in more than 50 years, from the experimental observations of electric field modulated spin waves as well as spin wave theories quantitative characterization of dynamic ME coupling in FE/FM heterostructures is expected. In this work, we conduct the PSWS measurements in CoFeB/(011) PMN-PT structure to determine the electric field induced shift of spin wave frequencies and by fitting the experimental results to spin wave equation the electric field induced change in anisotropy field is also calculated.

Device structure for PSWS measurements is shown in Fig. 1(a). Ferroelectric (011) cut PMN-PT [xPb(Mg1/3Nb2/3)O3-(1 − x)PbTiO3] (x ~ 0.68) substrates with dimensions of 20 (L) × 10 (W) × 0.5 (H) mm^3 were purchased. Au electrode was sputtered onto the bottom of the (011) PMN-PT substrate. 30 nm thick CoFeB film was directly sputtered on the top of the PMN-PT substrate followed by depositing 190 nm thick SiO2 layer. Then, a pair of gold coplanar strip-lines (antennae) was patterned on the SiO2 layer in order to excite at one antenna and detect at the other the spin wave signals. The width of the strip lines and their separation in each antenna were both 4.0 μm and the edge-to-edge gap between both antennae was also 4.0 μm. The ends of both strip lines were shorted for high efficiency purpose. As for the samples used for in-plane MOKE measurement, a 190 nm thick SiO2 layer was inserted between PMN-PT substrate and CoFeB layer to form CoFeB/SiO2/PMN-PT structure.

For all electric field modulation measurements, external voltage was applied to bottom Au electrode and along film thickness direction, while ferromagnetic layer was electrically grounded. External magnetic field was applied along in-plane (01-1) direction of the PMN-PT crystal. HP 8722ES two-port s-parameter vector network analyzer (VNA) was used for the PSWS measurements. Each port of VNA was connected to one antenna in order to generate and detect spin waves. The direction of bias magnetic field was applied.

Quantitative analysis of electric field induced change in anisotropy field in CoFeB/(011) xPb(Mg1/3Nb2/3)O3-(1 − x)PbTiO3 (x ~ 0.68) heterostructures

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Electric modulation of spin waves in ferroelectric/ferromagnetic heterostructures has attracted much attention due to its potential in spin wave devices. In this letter, we report our work on quantitating the electric field induced modulation of spin wave frequency and anisotropy field in CoFeB/(011) PMN-PT structure by propagating spin wave spectroscopy (PSWS) technique. To verify the reliability of PSWS measurements, magneto-optical Kerr effect measurement is also performed, the result of which is comparable with that from the PSWS measurement.
along the surface of the ferromagnetic film but perpendicular to the propagation direction of the excited spin waves, so surface mode spin waves were detected for current configuration. To ensure uniform magnetization in ferromagnetic layer during the measurement, the external bias magnetic field was applied and swept from 500 to 0 Oe by step of ~5.0 Oe. At each bias magnetic field, the VNA swept the frequency between 1.0 GHz and 7.5 GHz with input power of −10 dBm (0.1 mW) at one antenna and simultaneously recorded the excited spin waves at the other.

Before PSWS and MOKE measurements, the in-plane strain-voltage (s-V) characteristics were measured by mounting a biaxial strain gauge (Micro-Measurements) on CoFeB/(011) PMN-PT/Au sandwich structure. The strain shows different change with the applied voltage along different in-plane crystal orientation, (01-1) and (100). Typical results are shown in Fig. 1(b). Along the in-plane (01-1) direction, tensile strain is observed, that is, with the application of the electric field, the dimension along (01-1) direction increases. However, along the in-plane (100) direction, compressive strain is obtained indicating the decreased dimension along (100) direction with the applied voltage. Sharp peaks (or troughs) in the s-V loop along (01-1) (or (100)) direction occur during the transient state of ferroelectric switching in the PMN-PT substrate. To some extent, these peaks and troughs conceal the butterfly-like shape of the s-V measurements, which is usually observed in s-V measurements of most of ferroelectrics. The inset in Fig. 1(b) is the magnification of the s-V loop along in-plane (01-1) direction and the blue curves are plotted for eye guide to show the inverse butterfly shape hidden behind the abnormal peaks caused by ferroelectric switching.

Typical PSWS spectrum is shown in Fig. 2(a), where a bias voltage of 150 V is applied and the S$_{12}$ amplitudes are recorded and plotted as a function of external magnetic field and frequencies of the exciting electric field. Strong spin wave features are well visualized and the observable SW frequency increases with the increase of external magnetic field. According to the theory of surface mode spin waves, SW frequency $f$ is determined by

$$f^2 = \left(\frac{\gamma}{2\pi}\right)^2 \left[H_o^2 + H_{ani}^2 + 4\pi M_s + H_{ani}(H_{ani} + 4\pi M_s)\right] + \frac{(4\pi M_s)^2}{4} \left(1 - e^{-2\pi d}\right),$$

where $H_o$ is the external bias magnetic field, $H_{ani}$ the anisotropy field of ferromagnetic film, $M_s$ the saturation

FIG. 1. Device structure for PSWS measurements (a) and the in-plane strain measurement in CoFeB/(011) PMN-PT/Au sandwich structure (b). The inset in Fig. 1(b) is a magnification of the s-V loop along in-plane (01-1) direction. The blue curves were drawn to guide eyes to show a inverse butterfly shape.

FIG. 2. S$_{12}$ response map (a) and SW frequency-voltage dependence (b) measured by the VNA in CoFeB/(011) PMN-PT composite structure. (a) was imaged while an external voltage of 150 V was applied. In (b), external voltage was applied between 200 and −200 V.
magnetization, $k$ the in-plane wave vector ($\sim 625 \text{ cm}^{-1}$ here), $d$ the thickness of the ferromagnetic film (30 nm), and $\gamma$ the gyromagnetic ratio. Due to the strain coupling at FE/FM interface, the anisotropy field $H_{\text{ani}}$ in ferromagnetic phase will be changed during the application of the external voltage across the ferroelectric phase, which has been observed by static MOKE measurements. According to Eq. (1), SW frequency also changes with $H_{\text{ani}}$, resulting in electric field induced mediation of SW frequency. This result is shown in Fig. 2(b). An external voltage is applied to the ferroelectric phase resulting in the change in polarization state and then the strain at FE/FM interface. At each polarization state corresponding to each preset voltage step, $S_{12}$ response spectrum is recorded as a function of bias magnetic field and excitation frequency. Fig. 2(b) indicates the voltage-dependent SW frequencies at bias magnetic fields of 100 and 150 Oe. Both frequency-voltage loops show inverse butterfly shape and follow the shape of s-V characteristic along in-plane (01-1) direction except for those sharp peaks caused by ferroelectric switching in Fig. 1(b). These butterfly loops indicate the essence of strain-induced ME coupling. Note that in Fig. 2(b), no abnormal peaks are observed during ferroelectric switching, different from those distinct peaks from the s-V measurement along in-plane (01-1) direction shown in Fig. 1(b). In PSWS measurements, at each electrical polarization state of ferroelectric phase, it takes as long as 16 min to get the whole $S_{12}$ spectrum, so PSWS technique works at stable polarization state and the influence of dynamic ferroelectric switching on SW propagation and then $H_{\text{ani}}$ is greatly reduced.

To well understand both butterfly loops in Fig. 2(b), we define two scanning directions: forward scan, the external voltage is applied from +200 to −200 V; while backward scan, the voltage is from −200 to +200 V. In the forward scan, (011) PMN-PT substrate is first positively polarized by +200 V for 5 min, then the external voltage is applied by voltage increment of −10 V from 200 to −200 V. At positive polarization state of the ferroelectric phase from 200 to −70 V, SW frequency decreases from 4.05 to 3.63 GHz at $H_o$ of 100 Oe and from 4.72 to 4.23 GHz at $H_o$ of 150 Oe, corresponding to averaged SW frequency modulation of 1.69 MHz/V. At external voltage of −70 V, ferroelectric switching occurs. SW frequency increases with the further decrease of external voltage from −70 to −200 V. The backward scanning process indicates nearly the same SW frequency-voltage dependence except a little large frequency modulation of 2.80 MHz/V in negative polarization state between −200 and 80 V. This inconsistency of frequency modulation at positive and negative polarization states may be due to the asymmetric polarization in ferroelectric phase which results in asymmetric strain.

The square of SW frequencies obtained in our measurements is plotted as a function of the external magnetic field and shown in Fig. 3(a). With the decrease of the external voltage from −50 to −200 V, $f^2$-$H_o$ curve shifts upward due to electric field induced change in anisotropy. By fitting $f^2$-$H_o$ relation with Eq. (1), the values of $(2H_{\text{ani}} + 4\pi M_s)$ can be determined from the fitting coefficient, $P_1$, of the first-order term in Eq. (1). Though the fitting curves in Fig. 3(a) seem linearly dependent on $H_o$ and parallel to each other, precise calculation indicates that the fitting coefficient $P_1$ does not keep constant during the application of the applied voltage. The saturation magnetization $M_s$ of ferromagnetic film is not tuned by the applied voltage, so the change in $P_1$, $\Delta P_1$, with applied voltage is directly related to the change in anisotropy field $\Delta H_{\text{ani}}$ ($\Delta H_{\text{ani}} = \Delta P_1/2$), where $\Delta H_{\text{ani}}$ is the difference in $H_{\text{ani}}$ between a given voltage and 0 V. From this deduction, we can easily quantitate the change in $H_{\text{ani}}$ with the applied voltage. The relative permeability of CoFeB layer is frequency dependent. Here, we use the value of 120 at $\sim 3.75 \text{ GHz}$ for our calculation. This quantitative result is shown in Fig. 3(b). $\Delta H_{\text{ani}}$-voltage curve reveals clear inverse butterfly shape indicating the strain-induced ME coupling. The minimum $\Delta H_{\text{ani}}$ occurs at voltage of −70 V and +80 V, consistent with the voltages corresponding to the minimum SW frequencies shown in Fig. 2(b). The maximum change in $\Delta H_{\text{ani}}$ is about 19.06 Oe. During the forward scan, at the positive polarization state between 200 and −70 V, $H_{\text{ani}}$ decreases with the decrease of the applied voltage corresponding to a ME coupling coefficient of 3.49 Oe cm/kV; while at the ferroelectric switching transient from −70 to −200 V, $H_{\text{ani}}$ increases with further decrease of the applied

![FIG. 3. $f^2$ as a function of external magnetic field (a) and the change in anisotropy field $\Delta H_{\text{ani}}$ with the applied voltage (b). In (a), open circles are data obtained from PSWS measurements at applied voltages of −200, −150 and −50 V, while solid curves are fitting results according to Eq. (1).](image)
voltage corresponding to a much larger ME coupling of 7.06 Oe cm/kV. Similarly, during the backward scan, \( H_{ani} \) decreases with the increase of the applied voltage from -200 to 80 V with a ME coefficient of 2.75 Oe cm/kV and then increases with the further increase of applied voltage from 80 to 200 V corresponding to a ME coefficient of 5.44 Oe cm/kV at the transient state of ferroelectric switching. Here, we do not use the constant term \( P_2 = -H_{ani}(H_{ani} + 4\pi M_s) + \frac{4\pi M_s}{B} \left(1 - e^{-2kd}\right) \) in Eq. (1) to quantify \( \Delta H_{ani} \) just because \( P_2 \) includes two variables, \( H_{ani} \) and \( d \). During the application of the external voltage, the thickness of the ferromagnetic film is also changed due to the reverse piezoelectricity. The change in film thickness \( \Delta d \) contributes to the change in \( P_2 \) with the same order of magnitude as the \( \Delta H_{ani} \)-caused change in \( P_2 \) and thus the influence of \( \Delta d \) cannot be neglected during the determination of \( H_{ani} \).

To further verify the change in anisotropy field with the applied voltage, in-plane MOKE experiments were performed in CoFeB/SiO\(_2\)/PMN-PT/Au structures to qualitatively characterize the change in anisotropy field by static ME coupling measurements. In our measurements, external magnetic field was applied along the in-plane \( \langle 01-1 \rangle \) direction of the PMN-PT crystal. The change of normalized Kerr rotation hysteresis (M-H) loops with the applied voltage is shown in Fig. 4(a). The external voltage from 0 to -400 V causes the inverse of the loop body from rounded to nearly rectangular shape and also the increase of the coercive electric field \( H_c \). Quantitative analysis of the voltage-induced change in \( H_c \) is shown in Fig. 4(b). \( H_c \)-voltage loop displays the inverse butterfly shape following the evolution of the s-V loop obtained along the in-plane \( \langle 01-1 \rangle \) direction in Fig. 1(b). \( H_c \) decreases linearly from 37.3 to 22.1 Oe during positive polarization state in the forward scan and from 37.7 to 25.0 Oe during negative polarization state in the backward scan. The sharp peaks observed between -60 and -200 V in the forward curve and between 80 and 200 V in the backward curve are also observed in both capacitance-voltage and in-plane strain-voltage measurements and attributed to the occurrence of dynamic ferroelectric switching in the ferroelectric phase.\(^{14,15}\) In our MOKE measurements, it only takes about 15 s to get a whole M-H loop, thus strain relaxation during ferroelectric switching is well reflected in the MOKE result and the \( H_c \)-voltage characteristic follows the shape of strain-voltage loop along in-plane \( \langle 01-1 \rangle \) direction.

Though, from the MOKE measurements, we could not quantitatively determine the change in anisotropy field with the applied voltage, the change in \( H_c \) roughly scales with that of the anisotropy field. In the MOKE measurements, \( H_c \) decreases from 37.3 to 22.1 Oe with the decrease of the applied voltage from 400 to -60 V in the forward scan, and from 37.7 to 25.0 Oe with the increase of the applied voltage from -400 to 80 V in the backward scan. Thus, an average rate of 29.7 Oe/kV is calculated to determine the voltage-induced change in \( H_c \). Due to the voltage drop on SiO\(_2\) layer, the actual voltage applied on ferroelectric phase is lower than the apparent voltage shown in Fig. 4(b). Since ferroelectric switching induces the peaks in Fig. 4(b) and those troughs in Fig. 3(b) corresponding to this transient state, the voltage applied to the PMN-PT substrate should be equal to its coercive voltage. From Fig. 3(b), ferroelectric switching occurs at -70 V and +80 V, corresponding to external voltages of -140 V and +160 V applied to CoFeB/SiO\(_2\)/PMN-PT/Au structure in Fig. 4(b). So, as for the present CoFeB/SiO\(_2\)/PMN-PT/Au configuration, only half of the external voltage is applied to the ferroelectric phase. Considering the actual voltage drop on ferroelectric substrate, this average rate of 29.7 Oe/kV should be doubled, that is, 59.4 Oe/kV. Similarly, in the PSWS measurements, an average rate of 72.1 Oe/kV is observed from Fig. 3(b) to show the voltage-induced change in \( H_{ani} \). Both values are comparable. Here, we will not give a more detailed comparison because, as for the CoFeB/SiO\(_2\)/PMN-PT/Au structure in our MOKE measurements, we cannot well estimate to what extent the SiO\(_2\) layer influences the strain coupling between CoFeB and PMN-PT layers.

In summary, by propagating spin wave spectroscopy technique, electric field modulation of spin waves in CoFeB/(011) PMN-PT/Au heterostructures is characterized. The influence of electric field on spin wave frequency and anisotropy field is quantitatively analyzed via dynamic PSWS measurements and also spin wave theory. MOKE measurements are performed to verify the results from PSWS measurement. Our observation indicates via PSWS method
dynamic ME coupling coefficient and spin wave frequency modulation can be well quantitated.

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