Spin waves in CoFeB on ferroelectric domains combining spin mechanics and magnonics

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Abstract

Spin dynamics controlled by magnetoelastic coupling and applied electric fields might play a vital role in future developments of magnonics, i.e., the exploitation of spin waves for the transmission and processing of information. We have performed broadband spin-wave spectroscopy on a magnetostrictive CoFeB alloy grown on a ferrolectric $BaTiO_3$ substrate causing elastic strain with a quasi-periodic modulation. We find characteristic eigenfrequencies and spin-wave modes with large group velocities and small damping. These results suggest bright perspectives for electric-field control of reprogrammable magnonics.

Keywords: A. ferroelectric; A. ferromagnetic; D. magnetoelectric coupling; D. magnonics;

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1. Introduction

Reconfigurable magnonic crystals [1, 2, 3, 4, 5, 6] and meta-materials [7] operating in the GHz frequency regime have attracted great interest recently. Periodically patterned ferromagnets [Fig. 1 (a) and (b)] or periodic arrangements of tailored magnetic domains [Fig. 1 (c) and (d)] offer artificially tailored band structures for spin waves (magnons) that are modified using a magnetic field [2, 6, 8]. These intriguing characteristics have further

Figure 1: Periodic array of bistable ferromagnetic nanostripes (bright) in (a) saturated and (b) demagnetized states where the unit cell of the magnonic crystal is composed of two antiparallel nanostripes. Periodic domain configuration at (c) zero and (d) finite applied magnetic field. The blue stripes indicate domain walls. In (b) and (d) magnetic fields are used to reconfigure the unit cell of the periodic lattice by conventional means. (e) Magnetic stripe domains formed on a ferroelectric substrate (or film) with in-plane ferroelastic a_1 and a_2 stripe domains. Domain pattern transfer in this hybrid system is obtained by strain transfer and inverse magnetostriction. (f) A bias voltage V applied between the top ferromagnet and a conducting back gate (green) provokes an out-of-plane rotation of the ferroelectric polarization vector, thereby modifying the in-plane lattice symmetry of the tetragonal crystal. Strain transfer to the ferromagnet induces both a rotation of the magnetization in each stripe domain and a change of the magnetic anisotropy strength. The green and red arrows indicate the orientation of magnetization on top of the a_1 and a_2 domains, respectively. Blue and gray arrows indicate electrical polarization vectors and thereby the long axis (c axis) of the tetragonal unit cell of the ferroelectric material.

fueled the idea of magnonics where spin waves are used to transmit and process information without moving charges [9, 10]. So far, quasi-static [2] or radiofrequency (rf) [11] magnetic fields have been used to both reprogram the magnetic configurations and achieve different dynamic responses. Control via magnetic fields, however, requires current flow which introduces heat dissipation. To realize magnonic devices offering low power consumption, alternative routes for magnetization and spin wave control need to be explored. Here, spin mechanics can play a vital role. As a promising route a hybrid approach has been proposed where a ferromagnet is controlled via a piezoelectric underlayer [12]. In this configuration, an electric field changes the elastic strain provided by the underlayer, which modifies the magnetic anisotropy [13] and correspondingly the spin-wave properties of the ferromagnet. Piezoelectrically controlled ferromagnetic resonance has already been established [14, 15]. Magnonic devices might be even further advanced using reprogrammable states provided by coupling to ferroelastic domains of a ferroelectric substrate or underlayer. For example, being in the tetragonal phase at room temperature, $BaTiO_3$ with in-plane polarization contains a regular pattern of a_1 and a_2 stripe domains as schematically shown in Fig. 1 (e). These domains have recently been found to induce a spatially varying magnetic anisotropy via inverse magnetostriction in e.g. CoFe, which can result in full imprinting of a_1 and a_2 stripe domains into ferromagnetic films [17, 16] [Fig. 1 (e)]. An electric-field induced rotation of the ferroelectric polarization vector modifies the orientation of the tetragonal $BaTiO_3$ lattice. As a consequence, the elastic strain and the magnetic anisotropy of the ferromagnet change. For the scenario of Fig. 1 (f), i.e. an electric-field induced rotation of the ferroelectric polarization out of the substrate plane, it has been reported that the easy magnetization axes of the stripe domains rotate by 90 deg and the strength of the uniaxial magnetic anisotropy enhances significantly [18, 19]. Electric-field controlled spin mechanics based on such a hybrid ferromagnetic-ferroelectric approach [20] is suggested to offer improved functionality of magnonic devices with potentially even lower power consumption.

In this paper, we investigate the dynamic response of cobalt iron boron (CoFeB) grown on a ferroelectric $BaTiO_3$ substrate with alternating a_1 and

a_2 stripe domains. Providing small spin-wave damping and large spin-wave group velocities the magnetically isotropic alloy CoFeB has already been found to be attractive for magnonics [21]. In this work we make use of the magnetostrictive properties of CoFeB and demonstrate that the ferroelastic $BaTiO_3$ domain pattern is fully transferred to a 50 nm thick CoFeB film [Fig. 1 (e)]. Performing broadband spin-wave spectroscopy in the GHz frequency we find two prominent branches that reflect resonant spin excitations in regions of different magnetic anisotropy. We attribute the branches to the ferromagnetic stripe domains that form on the a_1 and a_2 domains of the ferroelectric substrate. We find large spin-wave group velocities and relatively small damping making such hybrid ferromagnetic-ferroelectric structures attractive for reprogrammable magnonics using electric instead of magnetic fields.

2. Experimental techniques

For the experiments, a 50 nm thick $Co_{40}Fe_{40}B_{20}$ film was grown on a $BaTiO_3$ single-crystal substrate with alternating a_1 and a_2 stripe domains using magnetron sputtering at 300 K [Fig. 1 (e)]. The ferroelastic stripe domains were 5 μm to 8 μm wide. Quasistatic magnetization reversal was investigated by magneto-optical Kerr effect (MOKE) microscopy (Fig. 2). Broadband spin wave spectroscopy [22] was performed with 9 mm long coplanar waveguides (CPWs) with different inner conductor widths w_c. The sample was placed face down (Fig. 3 (a)) in an in-plane magnetic field of up to 100 mT applied under different angles α. For $w_c = 20$ μm, the main excitation strength of the CPW was calculated to be at wavevector $|\overrightarrow{k}| = 0.096 \cdot 10^4 \frac{\mathrm{rad}}{\mathrm{cm}}$.

A microwave current provided by a vector network analyzer (VNA) generated a microwave field $\overrightarrow{h}_{\mathrm{rf}}$ around the CPW. $\overrightarrow{h}_{\mathrm{rf}}$ excited spin waves via the torque $\tau = d\overrightarrow{M}/dt = -|\gamma|\mu_0\overrightarrow{M} \times (\overrightarrow{h}_{\mathrm{rf}} + \overrightarrow{H}_{\mathrm{eff}})$ acting on the magnetization $\overrightarrow{M}$ (γ is the gyromagnetic factor and $\overrightarrow{H}_{\mathrm{eff}}$ the effective magnetic field). At the resonance frequency f the power transmission measured by the VNA is reduced. This absorption is marked by a dark contrast in the grey scale plots used in this paper. The sample is orientated in such a way that the excitation field $\overrightarrow{h}_{\mathrm{rf}}$ and the wavevector $\overrightarrow{k}$ are collinear to the ferroelectric stripe domains.

3. Results and discussion

For MOKE microscopy (Fig. 2), the magnetic field H was applied with an angle of 45 degree with respect to the ferroelectric stripe domains and collinear with the magnetic easy axis of the a_1 domains. At an external magnetic field of -60 mT the sample is homogeneously magnetized as the applied field exceeds the anisotropy field of the a_2 domains. The magnetization of the a_2 domains rotates towards its easy anisotropy axis when the field is reduced and the magnetic stripe pattern becomes visible. At +5 mT the magnetization of the a_1 domains switches and the a_2 domains gradually align with the field direction when H is increased further. The strengths of the strain-induced uniaxial magnetic anisotropies of the two domains differ slightly. From the slope of the hard-axis hysteresis curves (not shown) the following values are determined: $K_{\mathrm{a2}} = 2.2{\cdot}10^4\mathrm{J/m}^3$ and $K_{\mathrm{a1}} = 1.7{\cdot}10^4\mathrm{J/m}^3$. The corresponding anisotropy fields amount to 36.7 mT and 28.3 mT, respectively.

Figure 2: MOKE microscopy images of a 50 nm thick CoFeB film on $BaTiO_3$. The direction of H is along the vertical axis. The images in the upper (lower) rows are measured with the magneto-optical contrast axis along the vertical (horizontal) direction. The arrows indicate the direction of magnetization in the a_1 and a_2 domains.

Figure 3: (a) Sketch of the sample (red - $BaTiO_3$, blue - CoFeB) placed face down on the CPW consisting of three metallic leads. k denotes the transferred wave vector. (b) Field dependent grey scale plot. The excitation field of the CPW is collinear with the stripe domains. The external magnetic field is applied at an angle of 45 degree with respect to the stripe domains. The two prominent modes (marked blue and green) are attributed to the a_1 and a_2 magnetic stripes. (c) Field dependent grey scale plot of the same geometry but the external field direction is changed by 90 degree compared to the previous case. Two prominent modes occur again but the minima are located at slightly lower field strength.

Broadband spin wave spectra are summarized in Figure 3 where H is varied from -60 to +60 mT in steps of 0.5 mT. In Fig. 3 (b), we consider $\alpha = 45$ deg, i.e. the same field direction as in Fig. 2. Two prominent branches with different field dependencies are obtained. The resonance frequencies of the branch marked by squares increase with increasing H. Such a behavior is commonly attributed to a ferromagnet where H is collinear with the magnetic easy axis. The frequencies of the branch highlighted by dots, however, exhibit two minima. This contrasting behavior suggests H to be perpendicular to a magnetic easy axis [23]. Considering the magnetic stripe domains observed with MOKE we attribute the upper (lower) branch to spin excitations within the a_1 (a_2) domains. In Fig. 3 (c) we show data for $\alpha = 135$ deg. The most prominent modes exhibit a similar behavior compared to Fig. 3 (b). The minima positions are however shifted by a small amount. Their field values provide a measure of the anisotropy fields H_{ani}.

From Figs. 3 (b) and (c) we extract $\mu_0 H_{\mathrm{ani}}$ of 24 and 22 mT, respectively. These values are smaller than the anisotropy fields extracted from the slope of hard-axis magnetic hysteresis curves. Still, H_{ani} is larger for a_2 compared to a_1 domains. The linewidth of the resonances are about 400 to 600 MHz. This value is only slightly larger compared to a nominally identical CoFeB film grown on SrTiO_3 that exhibits a linewidth of 300 to 400 MHz in the saturated state.

In Fig. 4 we show the angular dependencies of the resonances taken at 60 mT. Two prominent modes are seen, both following a two-fold symmetry. The modes seem to cross near $\alpha = 0$ deg. Near $|\alpha| \approx 90$ deg the signal strength decreases as the excitation field $\overrightarrow{h}_{\mathrm{rf}}$ is almost collinear with the magnetization direction and the excitation torque is small. Still, we extract that the two modes do not cross at $|\alpha| = 90$ deg. We attribute this anticrossing behavior to interactions between neighboring stripes domains, which will be studied in detail elsewhere.

Figure 4: Angular dependence of the resonances at a constant magnetic field of +60 mT. The corresponding angles of the field dependent data of Fig. 3 are marked by dashed lines.

In the following we investigate the group velocity of spin waves in the hybrid ferromagnetic-ferroelectric sample. For this, we have taken spectra with two more CPWs exhibiting different inner conductor widths w_{c} of 4 μm and 160 μm. The wavevector of the 4 μm CPW was calculated to be $k_1 = 0.31 \cdot 10^4 \frac{\mathrm{rad}}{\mathrm{cm}}$. The wavevector k_2 for $w_{\mathrm{c}} = 160$ μm was about two orders of magnitude smaller, close to $k = 0$. In Fig. 5 (a) we show the eigenfrequencies f measured for the two different CPWs. They differ by a few 100 MHz over the full magnetic field range. The systematic difference suggests a finite slope $\frac{2\pi df}{dk}$ in the dispersion relation of the ferromagnetic material, i.e. a non-zero group velocity. Note that the wavevector is chosen to be perpendicular to the applied field, i.e., the magnetization M at large field. We thereby address so-called Damon-Eshbach modes. Using $v_\mathrm{g} = \frac{2\pi df}{dk} = \frac{2\pi\Delta f}{\Delta k}$ with $\Delta k = k_1 - k_2 \approx k_1$ we extract group velocities as summarized in Fig. 5 (b). With increasing field the group velocity reduces from about 14 km/s at $\mu_0 H \approx 0$ to 8 km/s at 100 mT. The relatively large values and the field-dependent variation are consistent with results obtained on another CoFeB alloy [21]. The large v_g make CoFeB interesting for applications in magnonics. In future experiments the presented hybrid sample is expected to allow for electric-field controlled spin-wave properties via a change in magnetic anisotropies (i.e., H_eff) after integration of a back-gate [cf. Fig. 1 (e) and (f)].

Figure 5: (a) Resonance frequency as a function of external magnetic field at $\alpha = 0$ deg for CPWs with w_c of 4 μm and 160 μm. (b) Group velocities extracted from (a).

4. Conclusions

In conclusion, we have reported on broadband spin-wave spectroscopy performed on CoFeB grown on ferroelectric $BaTiO_3$ exhibiting ferroelastic a_1 and a_2 stripe domains. Via inverse magnetostriction, the magnetic anisotropy of CoFeB is characteristically modulated leading to ferromagnetic domains with alternating in-plane magnetization directions. Our data substantiate low damping and large spin-wave propagation velocities in the quasi-periodic stripe domains offering new perspectives for electric-field control of magnonic

devices and artificial crystals in future experiments. We acknowledge financial support through the German priority program SPP 1538 spin caloric transport via project GR1640/5-1, the German excellence cluster Nanosystems Initiative Munich, the Academy of Finland under Contract No. 260361, and the European Research Council (ERC-2012-StG 307502-E-CONTROL). K.J.A.F. acknowledges support from the Finnish Doctoral Program in Computational Sciences. T.H.E.L. is supported by the National Doctoral Program in Materials Physics.

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