Excitation of coherent propagating spin waves in ultrathin CoFeB film by voltage-controlled magnetic anisotropy

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Spin waves (SWs) may be used as potential information carriers in next generation low-power spintronics devices. Here, we report an experimental study on the excitation of propagating magnetostatic surface SWs by voltage-controlled magnetic anisotropy in a 2 nm thick CoFeB film. The SWs are detected by a pico-second time-resolved longitudinal Kerr microscope with a spatial resolution of 600 nm. We found a linear increase in the SW amplitude with the applied rf voltage. We show that in this ultrathin film, the voltage excited SWs can propagate up to micrometer distances which decrease with the increase in the bias magnetic field value. This is also supported by micromagnetic simulation results. Furthermore, we show that voltage excitations are spatially localized as opposed to conventional microstrip antenna induced Oersted field excitations. We discuss about the advantage of voltage excitation compared to the Oersted field excitation. We believe that voltage excitation of SWs will be more suitable and useful for the development of all-voltage-controlled nanoscale spintronics devices with a high density of integration.

Spin waves (SWs) are the collective precessional motion of electrons’ spins in a ferromagnetic material. Information can be encoded and carried by either SW amplitude or SW phase up to macroscopic distances without flow of electronic charges. Therefore, these SW based spintronics devices are free from the energy dissipation due to Joule heating, which is one of the main drawbacks of modern electronic devices. Conventionally, SWs are excited by charge current generated rf Oersted fields, spin-transfer-torques (STT), femtosecond pulsed laser beams, and thermal means. However, Oersted fields are spatially distributed and therefore not suitable for the application in spintronics devices in sub-micrometer length scales. Although STT can be localized in sub-micrometer length scales, a high current density \( \sim 10^{10} \text{A m}^{-2} \) is generally required to excite detectable SWs, which causes joule heating. Moreover, the incoherent nature of STT excitation makes it difficult to control SW characters such as amplitude and phase for logic applications. Femtosecond pulsed laser beams also promise to be an efficient method for localized excitation of coherent SWs as laser pulses can be focused down to hundreds of nanometer length scale limited by diffraction. However, implementation of such pulsed laser beams for the development of practical SW based devices is difficult. The incoherent thermal excitations are also not suitable for future technology as they are associated with joule heating. As an alternative approach, magneto-electric coupling, which allows us to control magnetic properties (e.g., magnetic anisotropy) by the electric field, can be used to excite SWs.

A number of recent studies show that the perpendicular magnetic anisotropy (PMA) at a ferromagnetic metal (e.g., CoFeB) and nonmagnetic insulator (e.g., MgO) interface can be controlled through modulation of spin density in the Fe-3d orbital by voltage, i.e., electric field. This voltage-controlled magnetic anisotropy (VCMA) promises to excite uniform ferromagnetic resonance (UFMR) in ultrathin 3d-ferromagnets with ultralow power consumption as opposed to conventional charge current based excitation methods. Recent theoretical and simulation reports show parametric excitation of SWs by locally applying VCMA in a laterally confined waveguide. Another experimental report demonstrates that the quasi-uniform FMR and other higher order SW modes can be parametrically excited in a nanodisc by globally applying VCMA. The main drawback of this kind of nonlinear excitation is that the SWs can only be excited when the VCMA field becomes larger than a threshold value and the lateral dimension of the top gate electrode for excitation needs to be within few tens of nanometers in order to achieve a lower threshold field value. Moreover, the SW amplitude is not linearly proportional to applied voltage which makes it very difficult to implement these nonlinear SWs in magnetic logic devices where control of SW amplitude and phase is important. To overcome these difficulties, linear, i.e., coherent SWs can be used. However, there is no experimental report on the excitation of coherent propagating SWs by VCMA.

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Here, we report excitation of coherent propagating SWs by locally modulating interfacial PMA of an ultrathin CoFeB film by voltage. Figure 1(a) represents the schematic illustration of the SW device for voltage excitation and experimental setup. The devices were fabricated from multilayer film-stacking structures (nominal thicknesses in nanometers are stated within parentheses): Si-substrate/Ta(5)/Ru(10)/Ta(5)/Co_{20}Fe_{60}B_{20}(2)/MgO(2)/Al_{2}O_{3}(10), deposited by rf magnetron sputtering at room temperature at a base pressure of 10^{-9}Torr (see supplementary material). The SW waveguides with a dimension of 10 × 100 μm^2 were defined by maskless UV photolithography followed by Ar^+ ion milling down to the Si substrate. The top electrode and other contacts were made by maskless UV photolithography followed by deposition of Ti(5)/Au(200) by e-beam evaporation. Fabricated devices were post-annealed at 300°C in a vacuum under a perpendicular magnetic field of 600 mT for 1 h.

In our CoFeB film, demagnetizing field overcomes the PMA field (H_p), resulting in an in-plane easy axis of magnetization. This in-plane magnetic configuration is ideal for detecting magnetization dynamics by longitudinal MOKE, and weak magnetic anisotropy is suitable for exciting relatively larger precession angle of magnetization to enhance the signal to noise ratio. To excite SWs, rf voltage (V_rf) from a signal generator (via a variable electronic delay generator) was applied across the top electrode (2 × 10 μm^2) and waveguide. This rf voltage periodically modulates PMA of CoFeB underneath the top electrode. The SWs are excited and propagated along the waveguide (x-axis) when the frequency (f) of V_rf matches with the SW resonance frequency. The propagating SW signals were detected by a pico-second time-resolved magneto-optical Kerr-effect (ps-TRMOKE) microscope stroboscopically (supplementary material). As the modulation of PMA by V_rf is proportional to the static magnetization component along the out-of-plane direction (M_s), the bias magnetic field (H) was applied at a small angle (\phi \approx 5°) with respect to the film-plane in order to have a non-zero value of M_s [Figs. 1(a) and 1(b)].

To calculate excitation efficiency of SWs as a function of the SW wave-vector, we performed Fourier transform of electric field distribution of applied rf voltage along the waveguide (supplementary material). Figure 1(c) shows the SW excitation efficiency in our device becomes maximum at wavevector, k = 0, which corresponds to UFMR mode and drastically decreases with k before vanishing at k = 2π/w = 3.14 rad μm^{-1}, where w is the width of the top electrode.

In our experiment, H was generally set along the y-axis [Fig. 1(a)] to study magnetostatic surface SWs (MSSW). Figure 2(a) shows a typical time varying MSSW signal measured at \mu_0H = 30 mT, f = 1.65 GHz at a distance of 1 μm from the top electrode. To find out the SW amplitude, the data points are fitted with a time varying sinusoidal function given by

\[ A(f, t) = A_0 + A_1 \sin (2\pi f_{MSSW} t + \beta). \]

Here, A is the detected signal, A_0 is the offset, \beta is the initial SW phase, and A_1 is linearly proportional to the SW amplitude. To find out SW resonance frequency (f_{MSSW}), we measured SW amplitude (A_1) as a function of f. Figure 2(b) shows that maximum SW amplitude is observed at f = 1.65 GHz for \mu_0H = 30 mT. This means that f_{MSSW} is 1.65 GHz for \mu_0H = 30 mT. The resonance frequency (f_{UFMR}) corresponding to UFMR was also checked by measuring a control sample (supplementary material). In Fig. 2(c), we plot f_{UFMR} and f_{MSSW} as a function of \mu_0H and fit them with analytical Kittel’s formulae given by

\[ f_{UFMR}^2 = \left( \frac{\mu_0\gamma}{2\pi} \right)^2 H(H + M_{eff}), \]

and

\[ f_{MSSW}^2 = \left( \frac{\mu_0\gamma}{2\pi} \right)^2 \left[ H(H + M_{eff}) + \frac{1}{4} M_s M_{eff} (1 - e^{-2it}) \right], \]

respectively. Here, \gamma is the gyromagnetic ratio, t is the film thickness, M_{eff} (= M_s - H_p) is the effective saturation magnetization, and M_s is the saturation magnetization. Note that the frequency difference between MSSW and UFMR is very small due to smaller values of M_{eff} and kt. Therefore, the exact value of k for SWs cannot be determined from Kittel’s fitting. As the excitation efficiency is higher for lower k values [Fig. 1(c)], it can be said that SWs with lower k are excited in our device.

We also measured SW amplitudes (A_1) as a function of V_rf. For voltage excitation, the VCMA, i.e., equivalent rf magnetic field (H_{eq}), is linearly proportional to V_rf (Ref. 36). Therefore, SW amplitudes should also be proportional to V_rf, i.e., square root of P_rf in the linear regime of excitation. In
Theoretically, group velocity (\(V\)) passes through the origin and there is no threshold value of excitation frequency to determine \(f_{\text{MSSW}}\). Note that the fitted line shows that SW amplitude linearly increases with \(x\) for MSSW.1,40 Here, \(\lambda_d = \sqrt{\gamma \mu H / \mu_0 f_{\text{MSSW}}}\), and \(\lambda_d\) is the Gilbert damping parameter. The theoretical expression for \(\lambda_d\) can be obtained by using the relation \(\lambda_d = \sqrt{\gamma \mu H / \mu_0 f_{\text{MSSW}}}\). We calculated theoretical values of \(\lambda_d\) by considering the values of \(\gamma, M_s, M_{\text{eff}},\) and \(x\) obtained from the UFMR measurement of the control sample (supplementary material). In Fig. 3(b), we plotted the calculated theoretical values of \(\lambda_d\) as a function of \(H\), which shows that \(\lambda_d\) decreases monotonically with the increase of \(H\). Note that the theoretical curve is not a single line. The reason behind this broad theoretical curve is the possibility of exciting k-vectors in the range of \(0 < k < 3.14 \text{ rad \mu m}^{-1}\). Although theoretical results qualitatively reproduce the experimental results, there is a discrepancy between them, especially at higher values of \(H\). The theoretical values are valid only for point-like emitters and detectors.7 In our case, the dimension of the SW emitter, i.e., top electrode, is comparable to \(\lambda_d\). Moreover, at higher values of \(H\), the calculated values of \(\lambda_d\) become less than 1 \(\mu m\), which is very close to the spatial resolution of our setup (\(\sim 600 \text{ nm}\)). Hence, \(\lambda_d\) is overestimated in the experiment at higher values of \(H\). We also performed micromagnetic simulations to support our experimental results with a model sample as shown in Fig. 3(c) (supplementary material). In the simulation, the dimensions of excitation and detection area were kept the same as the experiment to mimic the exact experimental condition. Figure 3(b) shows that the simulation results for variation of \(\lambda_d\) with \(H\) match with the experimental results quite well.

One of the key points for successful implementation of SWs in sub-micrometer-scale spintronics devices is to spatially confine, i.e., localize the SW excitation area within the nanometer length scale. In the case of voltage excitation [Fig. 4(a)], the excitation area is expected to be strictly confined underneath the top electrode. On the other hand, for antenna excitation, some part of rf current generated Oersted fields...
may be distributed outside the stripline as schematically represented in Fig. 4(b). As a result, the effective area of excitation is generally larger than the stripline width unlike voltage excitation. This may affect the decay of the SW signal with the propagation distance. To understand the localization nature of voltage excitation, we compared decay of voltage excited SWs with the decay of antenna excited SWs. The experimental results [Fig. 4(c)] show that the amplitude of antenna excited SWs also decays exponentially with propagation distance like voltage excited SWs. However, for antenna excitation, couple of initial points do not follow the exponential decay function due to non-localized nature of the rf current generated Oersted field. On the other hand, decay of voltage excited SWs follows the single exponential decay function due to the localized nature of voltage excitation. This proves that the voltage excitation is more spatially localized than the antenna excitation. We also fitted the amplitude decay of antenna excited SWs with the single exponential decay function after removing two initial points and found out that the SW decay lengths for antenna excitation have almost the same value as the SW decay lengths for voltage excitation (supplementary material).

In summary, we have demonstrated the excitation of coherent propagating SWs by VCMA and studied their...
properties by optical detection. We have shown that the spin waves can propagate up to micrometer distances in this ultrathin film. Practical SW based logic devices rely upon generation, manipulation, and detection of SWs, and all these processes should be carried out on-chip. We have shown that the voltage excitation area can be localized within the micro-meter length scale unlike antenna excitation. In principle, the voltage excitation area can be further reduced and localized down to few tens of nanometers by simply reducing the dimension of the top electrode. Therefore, voltage excitation may be implemented in high-density nano-scale spintronics devices without any cross-talking among the devices. Recent studies also show the possibility of manipulating SWs\(^{39}\) and magnonic bands\(^{41}\) by VCMA. The SWs may also be detected sensitively by magnetic tunnel junction (MTJ), where the SW waveguide may be used as a free layer. The dimension of the top pinned/ reference layer, which also decides the dimension of the detector, may also be reduced down to few tens of nanometers. In this way, all-voltage-controlled on-chip nanoscale spintronics devices can be developed for next generation. Therefore, we believe that our study is a step towards the development of all-voltage-controlled SW based logic devices.

See supplementary material for (1) spin wave wave-vector for voltage excitation, (2) measurement of ferromagnetic resonance frequency, (3) evaluation of the Gilbert damping parameter, (4) static I-V characteristics, (5) confirmation of voltage excitation, (6) simulation and (7) experimental results on the decay of SWs with propagation distance, (8) decay of SWs for antenna excitation, (9) sample fabrication, and (10) experimental details.

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