Micromagnetic Simulation of Voltage-Induced Spin Wave Resonance Properties in Ferromagnetic Nanowires with Perpendicular Anisotropy

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A fundamental issue in developing spin wave (SW) devices with ultralow power consumption is exploring energy-efficient excitation with nanoscale spatial resolution. We numerically studied the voltage-induced excitation of a geometrically confined standing spin wave (SSW), which is suitable for the downsizing of various SW devices. The micromagnetic configuration of the excited SSW, the resonance spectrum, and the structural size effects were investigated. In addition, a possible application to a SSW-based logic operation was demonstrated in a nanowire with lateral dimensions of 20 nm × 100 nm.

Key words: spin wave, ferromagnetic resonance, magnetic anisotropy, micromagnetic simulation

1. Introduction

In solid-state physics, spin dynamics in magnetic nanostructures is an active research field¹⁻³⁾. In particular, the collective and coherent magnetization precession of spin waves (SWs) has attracted intense research interest^{4,5)}. The promising abilities of SWs have resulted in the novel research field of so-called magnonics⁶⁻⁸⁾, where the phase or amplitude of a propagating SW is used as a novel information carrier or a signal-processing medium. Energy-efficient excitation or manipulation of SWs is essential to exploit the potential ability of SW-based devices. Two different approaches to this problem, parametric pumping (PP)¹⁾ and voltage-controlled magnetic anisotropy (VCMA)⁹⁾, have been intensively studied over the past years. PP is based on the nonlinear aspect of the spin dynamics, resulting in the excellent frequency-resolved excitation of short wavelength SWs, as experimentally observed in ferromagnetic oxide yttrium iron garnet¹⁰⁻¹²⁾ and metallic thin films¹³⁻¹⁹⁾. Voltage-induced manipulations of magnetic properties have also been attracting intense research interest²⁰⁻²⁴⁾. The superior performance of VCMA has been experimentally confirmed as being an ohmic dissipation free excitation of the ferromagnetic resonance²⁵⁻²⁷⁾, as opposed to conventional Oersted fields. In particular, the cooperative performance of PP and VCMA can be effectively exerted in a material system with perpendicular magnetic anisotropy²⁸⁾. Recently, the parametric excitation of propagating SWs via VCMA has been investigated using both theoretical²⁹⁾ and numerical³⁰⁾ approaches. However, the long distance propagation of SWs is still a challenging issue. In this study, the possibility of spatially resolved excitation of geometrically confined standing spin waves (SSWs) in magnetic nanostructures is addressed. A fundamental SW-based logic operation and its design considerations are also studied in the context of an application.

2. Numerical Model

Figure 1(a) shows a schematic figure of the investigated device structure, which consists of a perpendicularly magnetized nanowire and an overlaid gate electrode to apply electric fields for the local modulation of the perpendicular magnetic anisotropy (PMA). The following structural and magnetic parameters were adopted in the present study assuming ferromagnetic nanowires with interface-induced perpendicular anisotropy, such as the CoFeB/MgO system: the film thickness was $t = 0.8$ nm, the saturation magnetization was $M_s = 1600$ emu/cm³, the exchange stiffness constant was $A = 1.0$ μerg/cm, the effective uniaxial perpendicular anisotropy field was $H_k = 20$ kOe, the gyromagnetic ratio was $\gamma = 1.76 \times 10^7$ rad/s·Oe, and the Gilbert damping constant was $\alpha = 0.01$. The electric field-induced modulation of the PMA was numerically modeled by the local sinusoidal H_k change using the amplitude of ΔH_k under the gate electrode. The assumed maximum value of ΔH_k (500 Oe) corresponds to an areal anisotropy energy change of 32.5 μJ/m², which is comparable to the experimentally reported values of several tens of μJ/m².^{24,31,32)} The dynamics of the SW caused by the electric field-induced PMA modulation was simulated by numerically integrating the Landau–Lifshitz–Gilbert equation. Subtle thermal agitation as a parallel PP seed was introduced via effective Langevin fields³³⁾. The Langevin fields with an amplitude based on fluctuation dissipation theorem and random orientation were applied to micromagnetic numerical cells at each time step³⁴⁾. The fourth-order Runge–Kutta method was adopted as a numerical scheme. The magnetization was assumed to be uniform along the film thickness and the wire width direction, taking into consideration that the dominant magnetization change was along the long axis of the nanowire. Therefore, the nanowire was discretized into a one-dimensional dipole array with a separation of 1 nm, and the dipole coupling was computed using an apparent surface charge model. A

Fig. 1 (a) Schematic of a ferromagnetic nanowire with an overlaid gate electrode for SSW excitation, (b) dependence of the precession amplitude on the excitation frequency, (c) micromagnetic configuration of the SSW, and (d) the frequency spectra of the magnetization precession under the gate electrode.

force-free boundary condition was assumed at the wire edge. The spatial discretization and the time step (10^{-15} s) were preliminarily optimized via the micromagnetic standard problem No. 4.³⁵⁾

3. Results and Discussion

Figure 1(b) presents the precession amplitude of the magnetization excited with a sinusoidal modulation of the perpendicular anisotropy field ($\Delta H_k = 500$ Oe) under a gate electrode with a width of $W_g = 10$ nm, located at the center of a wire with lateral dimensions of $20 \text{ nm} \times 100 \text{ nm}$. The in-plane component of the normalized magnetization m_y at the wire center is plotted as a function of the excitation frequency, f_{exc} . The precession amplitude sharply decays below the resonance region ($f_{\text{exc}} < 5.43$ GHz) while gradually decreasing above the resonance region. The resonance frequency, f_{res} of 5.44 GHz, is twice the excited precession frequency, as shown in the frequency spectra of the magnetization precession (**Fig. 1(d)**), calculated from the digital Fourier transform of m_y . The micromagnetic configuration of the magnetization precession exhibits a first-order SSW along the long axis of the wire, as shown in **Fig. 1(c)**. These results confirm that the additional in-plane shape anisotropy of ferromagnetic wires with a nanoscale finite length causes an anisotropic precession trajectory accompanied by a time-varying m_z component with a frequency that is twice the precession frequency, which is essential as a seed for parallel parametric excitation. The results also reveal that the parametrically excited SSW exhibits an

Fig. 2 Elliptic precession trajectory and phase relationship between the sinusoidal perpendicular anisotropy modulation and the magnetization components.

Fig. 3 SSW resonance properties at various external fields H_b applied along the long axis of the wire.

asymmetric resonance profile, similar to the case of a propagating SW³⁰. The relative phase relationship between the time-varying PMA, m_x , and m_z indicates an apparent negative susceptibility, as shown in **Fig. 2**. That is, the increase in the perpendicular anisotropy field H_k leads to a decrease in m_z , and vice versa, reflecting the coherent SW resonance behavior.

The external bias field H_b applied along the long axis of the wire causes an additional linear mode excitation of the SSW, where the precession frequency is the same as the excitation frequency, as shown in **Fig. 3**. Conversely, the parametric mode disappears for H_b larger than 200 Oe. It can be reasoned that the precession axis is inclined to the x -axis due to the application of H_b , which results in the disappearance of the double period change in m_z necessary for a parallel parametric excitation seed. As can be seen in **Fig. 3**, the resonance profile of the parametric mode is markedly narrower than that of the linear mode, which would be suitable for frequency-selective SW-based device operations. **Figure 4** compares the dependence of the resonance precession amplitude m_y on the PMA modulation amplitude ΔH_k for the parametric and linear excitation modes at $H_b = 100$ Oe. m_y for the linear mode

Fig. 4 SSW precession amplitude as a function of the sinusoidal anisotropy field amplitude ΔH_k for parametric and linear excitations.

linearly increases with increasing ΔH_k up to approximately 150 Oe and deviates from a linear response for larger ΔH_k . Conversely, the precession amplitude of the SSW in the parametric mode was found to be insensitive to the PMA modulation intensity for ΔH_k smaller than 350 Oe, resulting in mostly constant values of m_y due to the thermal disturbance. The observed threshold for triggering the parallel parametric excitation has been theoretically predicted for a propagating SW^{29,30}.

The dependences of the parametric excitation properties on representative structural parameters are presented in **Figs. 5** and **6**. **Figure 5(a)** compares the resonance profile of SSWs excited in wires with various wire lengths L_x and a fixed gate electrode width ($W_g =$

Fig. 5 Dependence of the SSW properties on the wire length L_x : (a) the resonance spectra and (b) the nonuniformity of the precession amplitude along the wire.

Fig. 6 Dependence of the SSW properties on the gate electrode width wire length W_g : (a) the resonance spectra and (b) the nonuniformity of the precession amplitude along the wire.

10 nm). The values of f_{opt} , at which the precession amplitude reaches its maximum value, increase from 4.8 GHz to 6.7 GHz with L_x decreasing from 150 nm to 50 nm, reflecting the dispersion relation between the SW length and the excitation frequency. The observed broad spectrum in the short length wire can be associated with the large amplitude precession, geometrically confined in the narrow region; $m_y = 0.45$ ($L_x = 50$ nm), $m_y = 0.16$ ($L_x = 150$ nm). **Figure 5(b)** shows the relative ratio of the precession amplitude at the center ($m_{y,\text{center}}$) and edge ($m_{y,\text{edge}}$) of the wire. The variation of the precession amplitude along the wire axis markedly decreases with decreasing L_x and closes to the ferromagnetic resonance mode.

Even though f_{opt} and the nonuniformity of the precession amplitude also depend on the gate electrode width W_g , as shown in **Fig. 6(a), (b)**, this dependency is relatively weak compared to that on the wire length. That is, the increase in the values of W_g , which ranged from 10 nm to 100 nm, resulted in 15% and 18% increases in f_{opt} and $m_{y,\text{edge}}/m_{y,\text{center}}$, respectively. **Figure 6(a)** shows that the precession amplitude monotonously increases with increasing W_g . These results indicate a spatial integration effect in the voltage-induced excitation of the SSW, which can be applied to a logic operation as follows.

Figure 7(b) presents the frequency spectra of the precession amplitude excited with two electrodes located 25 nm and 75 nm from the wire end (**Fig. 7(a)**). The values of L_x and W_g were chosen to be 100 nm and 10 nm, respectively. A bias field of 100 Oe was applied along the wire axis. The two plots show the results for the different phase differences $\Delta\phi$ ($=0, \pi$) between the sinusoidal anisotropy changes in the two electrodes.

Fig. 7 (a) Schematic of two-generator device. (b) Comparison of the frequency spectra between the in-phase ($\Delta\phi = 0$) and opposite-phase ($\Delta\phi = \pi$) excitations with two electrodes located along the wire.

Two resonance peaks similar to those excited with one electrode are observed in the in-phase excitation ($\Delta\phi = 0$). Conversely, no distinguished excitation of the SSW was caused by the opposite-phase excitation ($\Delta\phi = \pi$). This result indicates that opposite PMA changes at different positions cancel out through the wire for both of the linear and parametric mode excitations, which can be used as phases comparing microwave voltages.

Another example of spatial integration of the voltage-induced SSW excitation with two electrodes is demonstrated in **Fig. 8**. The same device structure, as that shown in **Fig. 7**, was assumed. When an in-phase PMA modulation with $f_{\text{exc}} = 5.44$ GHz was applied with two electrodes ($G_A:1, G_B:1$), a parametric SSW was excited with ΔH_k larger than 200 Oe. A micromagnetic configuration of the SSW excited with two electrodes is

Fig. 8 (a) Comparison between the SSW precession amplitude for the one-gate ($G_A:0, G_B:1$) and simultaneous two-gate ($G_A:1, G_B:1$) excitations. (b) Micromagnetic configuration of the SSW excited with two electrodes.

shown in **Fig. 8(b)**. Conversely, an SSW was not formed with a single-electrode excitation ($G_A:0, G_B:1$), even when ΔH_k was larger than twice the excitation threshold for the two-electrode excitation. Note that the precession amplitude for the single-electrode excitation was suppressed within the thermal noise level due to the existence of a threshold on the parallel parametric excitation. These results should be applicable to the AND gate operation for nanostructured SW logic devices. Noise floor for the ΔH_k lower than 200 Oe ($G_A:1, G_B:1$) was somewhat smaller than that shown in **Fig. 7** ($\Delta\phi = 0$), since the higher ΔH_k of 500 Oe was assumed in the spectra simulations of **Fig. 7**. The noise level of the single-electrode excitation also exhibits smaller value independent on the value of ΔH_k .

4. Conclusions

The voltage-induced excitation of geometrically confined SSWs in nanowires with perpendicular anisotropy was numerically studied via micromagnetic simulations. Sinusoidal modulations of perpendicular anisotropy fields were found to cause linear and parametric mode excitations of SSWs depending on the external field. The dependence of the SSW resonance properties on the structural parameters was systematically examined. A possible application to a SSW-based logic operation was demonstrated in a nanowire with lateral dimensions of $20 \text{ nm} \times 100 \text{ nm}$, where the spatial integration effect of the voltage-induced anisotropy modulation was used.

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