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Attenuation of propagating spin wave induced by layered nanostructures

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Spin wave attenuation in the layered $[\text{FeNi}/\text{Pt}]_6/\text{FeNi}$ thin films was investigated by the time-domain electrical measurement. The spin-wave waveform was detected with an asymmetric coplanar strip transmission line, as an induced voltage flowing into a fast oscilloscope. We report that the amplitude of a spin-wave packet was systematically changed by controlling the thickness of a platinum layer, up to a maximum change of 50%. The virtues of spin wave, ultrafast propagation velocity and non-reciprocal emission, are preserved in this manner. This means that the Pt layer can manipulate an arbitral power-level of spin-wave input signal (reliable attenuator).

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Spintronic integrated circuits harnessing spin-wave propagation have been of great interest for signal processing in virtue of ultrafast propagation and low power consumption.^{1–3} The spin-wave logic gates have been recently demonstrated by using the Mach-Zehnder interferometer with yttrium iron garnet (YIG) waveguides.³ Since the YIG is not compatible with standard silicon integrated circuit (IC) technology, spin wave propagation in IC-compatible materials such as FeNi is of importance for the realization of integrated circuits.^{4–14} The magnetostatic surface wave (MSSW) in the FeNi film is the promising mode due to its high propagation velocity and a non-reciprocal character, which was also observed a long time ago in YIG films.^{3–5} As revealed in the previous letter,⁶ the non-reciprocal emission can be utilized for an initial input, since the non-reciprocal parameter (κ) is unchanged even if a spin wave propagates a long distance. For the signal processing with spin wave, furthermore, the control of spin wave amplitude after the emission is of great importance.

In this Letter, we report an attenuation control method of spin-wave packet in FeNi/Pt-based thin films. The amplitude attenuation is caused by the dissipation of the magnetic energy into the environment and thus related to the intrinsic damping. By utilizing the ferromagnetic-normal metal (F-N) interface coupling, we achieved amplitude change of spin waves without influencing the main virtues of spin waves: ultrafast propagation, and non-reciprocal emission.

Spin-wave medium consist of $[\text{Fe}_{17}\text{Ni}_{83}/\text{Pt}]_6/\text{Fe}_{17}\text{Ni}_{83}$ multilayer stacks grown by magnetron sputtering on intrinsic silicon substrates (see Table I) without annealing process. Here, the numbers in parentheses indicate the thickness of each layer in the unit of nm. The volume content of Pt is controlled from 0% to 10%, while the total thickness is kept constant at 35 nm (No. 1 to No. 5). The thickness of Pt layer (t) in each medium was set to be much thinner than the spin diffusion length ($\lambda_{sd} \sim 15$ nm), while those of FeNi are approximately the same as the spin diffusion length ($\lambda_{sd} \sim 5$ nm). The saturation magnetization was proportional to the volume

amount of FeNi layer, namely, the normalized magnetization curves of $[\text{Fe}_{17}\text{Ni}_{83}/\text{Pt}]_6/\text{Fe}_{17}\text{Ni}_{83}$ medium are all identical, and a negligible magnetic anisotropy was observed (see inset of Fig. 1).¹⁵

The time-resolved propagating spin wave spectroscopy (PSWS) was carried out for the multilayer stacks patterned into $120\text{ }\mu\text{m} \times 100\text{ }\mu\text{m}$ stripes. Spin waves (MSSW) are excited and detected with a pair of asymmetric coplanar strip (ACPS) transmission lines placed on the film (see Fig. 1), with applying the external magnetic field $H_{ext} \sim 100$ Oe parallel to the ACPS. A voltage pulse launched into the excitation ACPS generates a spin-wave packet, which induces a voltage on the detection ACPS connected to a 20 GHz sampling oscilloscope. The detail geometry of ACPS and experimental method are the same as reported in the previous letters.^{6,7} Spin wave wavevector $k \sim 0.5\text{ }\mu\text{m}^{-1}$ is determined by the ACPS geometry, which corresponds to the resonant frequency of approximately $\omega/2\pi \sim 3.6$ GHz. The spin wave frequencies were not changed even if we changed the Pt content. Experimentally, due to the mutual configuration between magnetization M and wave vector k , the spin-wave packet can be measured by four different excitation configurations: (M, k) , $(-M, k)$, $(M, -k)$, $(-M, -k)$, where the direction of M is set by the external in-plane field, H_{ext} .

Figure 2(a) represents the time-resolved waveforms for the patterned media with different contents of Pt (0%, 2%, 5%, and 10%). With increasing the content of Pt, the packet

TABLE I. List of FeNi-based medium.

Film no.	Layered structure (nm)	Content of Pt (%)
1	$\text{Fe}_{17}\text{Ni}_{83}(35)$	0
2	$[\text{FeNi}(4.95)/\text{Pt}(0.058)]_6/\text{FeNi}(4.95)$	1
3	$[\text{FeNi}(4.90)/\text{Pt}(0.117)]_6/\text{FeNi}(4.90)$	2
4	$[\text{FeNi}(4.75)/\text{Pt}(0.292)]_6/\text{FeNi}(4.75)$	5
5	$[\text{FeNi}(4.50)/\text{Pt}(0.583)]_6/\text{FeNi}(4.50)$	10

FIG. 1. Emission of spin-wave packet within FeNi-based films. A spin-wave packet is excited by a local magnetic field and detected as an induced voltage. (Inset) Optical micrograph of the patterned sample with a pair of asymmetric coplanar strip (ACPS). The ACPSs are comprising a signal line ($w_1 = 3 \mu\text{m}$) and a ground line ($w_2 = 9 \mu\text{m}$) with a separation length $w_3 = 2 \mu\text{m}$. (Inset) Normalized magnetization of the layered medium.

shows a distinct decay of amplitude without changing its envelope position. The envelopes of packets are well characterized by the Gaussian function $y = A \exp\left[-\left(\frac{t-t_0}{\tau}\right)^2\right]$, where A is the amplitude, t_0 is the center of packet, and τ is the decay time.

In Figs. 2(b) and 2(c), the A and t_0 are plotted as a function of the propagation distance. As clearly seen, the decay ratio increases with increasing the content of Pt (Fig. 2(b)), while the center position of the spin wave packet does not depend on the Pt content (Fig. 2(c)). The spin wave attenuation length (Λ) is determined by the exponential fitting using the formula $A \exp(-x/\Lambda)$, and the group velocity (v_g) by the linear slope of the delay. The Λ and v_g for all the excitation configurations are deduced and plotted as a function of Pt content. With increasing the Pt content from 0% to 10%, the attenuation length Λ is systematically decreased from $13 \mu\text{m}$ to $6.5 \mu\text{m}$, showing 50% change of amplitude [see Fig. 2(d)]. The group velocity, on the other hand, is approximately constant of 11.7 km/s [see Fig. 2(e)]. This means that the Pt layer can change spin wave attenuation with preserving the ultra-fast propagating velocity.

Note that the attenuation of the spin wave is directly connected with the damping parameter of the system. We can estimate the effective damping parameter from the attenuation length Λ . As shown in Fig. 3(a), a damping parameter is deduced to be 0.01 for the FeNi film (0%), showing a good agreement with reported damping α_0 .^{16–18} The effective damping slightly increases in the range of 0–2% Pt content, while it increases rapidly if the Pt content exceeds 2%.

The enhancement of Gilbert damping would be caused by two reasons. It is known that the damping of FeNi films is enhanced when it is attached by a heavy metal like Pt,^{19,20}

FIG. 2. (a) Time-resolved waveforms of a propagating spin-wave packet excited in FeNi-based films as a function of Pt content. The spin wave is excited with (M, k) configuration and detected at the propagating distance of $15 \mu\text{m}$. (b) Spin wave amplitudes and (c) center position with different gap distances, exhibiting an exponential decay and a linear increase, respectively. (d) Spin wave attenuation length and (e) group velocity for all excitation configurations.

caused by the spin pumping mechanism.²¹ However, it would be uneasy to directly apply this spin pumping mechanism to our experiment since the Pt layers are extremely thin. Another possible reason of the enhanced damping is that the Pt would act as a dopant into the FeNi films. It is consistent with previous studies^{22,23} where heavy-metal dopants in FeNi can increase the damping.

Finally, we discuss the non-reciprocity characterized by the parameter: $\kappa(M) \equiv A_{-k,M}/A_{k,M}$ and $\kappa(-M) \equiv A_{k,-M}/A_{-k,-M}$.⁶ As shown in Fig. 3(b), in the range of 0%–2%, the κ shows gradual decrease from 0.67, showing 4.5% change. This detail mechanism is left to be elucidated; however, the non-reciprocal parameter is approximately found to be constant $\langle \kappa \rangle = 0.62$ if the Pt content exceeds 2%. This average value agrees to the previous report, meaning the κ is only determined by the geometry of ACPS.

FIG. 3. (a) Effective damping parameter as a function of Pt content. (b) Non-reciprocal parameter (κ) as a function of Pt content. The $\kappa(M)$ and $\kappa(-M)$ are observed to be equivalent for each medium. The κ is averaged over the propagation distances except for the data at 30 μm , which introduces only a large error.

In conclusion, we have shown that we can systematically change the amplitude of spin-wave packet by inserting Pt layer, with preserving the ultrafast propagation velocity and the non-reciprocal emission. Thus, our findings lead to the spin-wave function as a signal attenuator for logical spin-wave circuits.

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