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Study of spin dynamics and damping on the magnetic nanowire arrays with various nanowire widths

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ABSTRACT

We investigate the spin dynamics including Gilbert damping in the ferromagnetic nanowire arrays. We have measured the ferromagnetic resonance of ferromagnetic nanowire arrays using vector-network analyzer ferromagnetic resonance (VNA-FMR) and analyzed the results with the micromagnetic simulations. We find excellent agreement between the experimental VNA-FMR spectra and micromagnetic simulations result for various applied magnetic fields. We find that the same tendency of the demagnetization factor for longitudinal and transverse conditions, N_z (N_y) increases (decreases) as increasing the nanowire width in the micromagnetic simulations while N_x is almost zero value in transverse case. We also find that the Gilbert damping constant increases from 0.018 to 0.051 as the increasing nanowire width for the transverse case, while it is almost constant as 0.021 for the longitudinal case.

Ferromagnetic nanostructures have recently attracted much interest for the wide potential applications in high density spintronic information storage, logic devices and various spin orbit torque phenomena [1–5]. It is well known that the detail spin dynamics of nanostructure is far from the one of the bulk's because of many reasons, different boundary conditions, changes of the magnetic properties including the saturation magnetization, anisotropy energy, and exchange stiffness constant, etc. Since the magnetic properties are usually sensitive functions of the sample fabrication conditions, it has been widely accepted that the detail sample fabrications are also important in the study of spin dynamics. However, the relatively less caution has been made for the boundary conditions of the spin dynamics in the nanostructure.

In the spin transfer torque magnetic random access memory (STT-MRAM), the magnetic damping constant is important because the switching current density is proportional to the damping constant [6]. In the nanowire, damping constant also plays crucial role in the spin dynamics including domain wall motion with magnetic field [7] and spin transfer torque [8]. Furthermore, it is the most important material parameter in spin wave (SW) dynamics [9]. Despite of the importance of the damping constant, many studies about spin dynamics in ferromagnetic nanowires have not taken into account the damping constant properly [10–12]. Only a few studies paid attention to the magnetic damping in the nanowires spin dynamics [13,14].

In this study, arrays of CoFeB nanowires are prepared by e-beam lithography, and they are covered coplanar wave-guide for the ferromagnetic resonance (FMR) measurement as shown in Fig. 1. We measured FMR signal with longitudinal (wire direction) and transverse rf-magnetic fields in order to investigate the spin dynamics with different boundary conditions. Also we extract Gilbert damping constant using micromagnetic simulations with the different applied magnetic field directions in various nanowire arrays. We find the damping constant increases with increasing the nanowire width for the transverse magnetic field with constant input damping constant in micromagnetic simulations, while we obtain almost constant damping constant for the longitudinal magnetic field.

The films were prepared using DC magnetron sputtering. The stacks consist of Ta (5 nm)/$Co_{16}Fe_{64}B_{20}$ (30 nm)/Ta (5 nm) on single crystal MgO (001) substrates. The films are patterned as 100-nm-width wire arrays with 200-nm-space each wires using e-beam lithography and an Ar ion milling technique as shown in Fig. 1. The width is determined with a scanning electron microscope (SEM). These nanowire arrays are covered by coplanar wave guide in order to characterized with the Vector Network Analyzer (VNA)-FMR technique described elsewhere [15]. We prepare nanowire arrays as shown in Fig. 1, and external DC magnetic field

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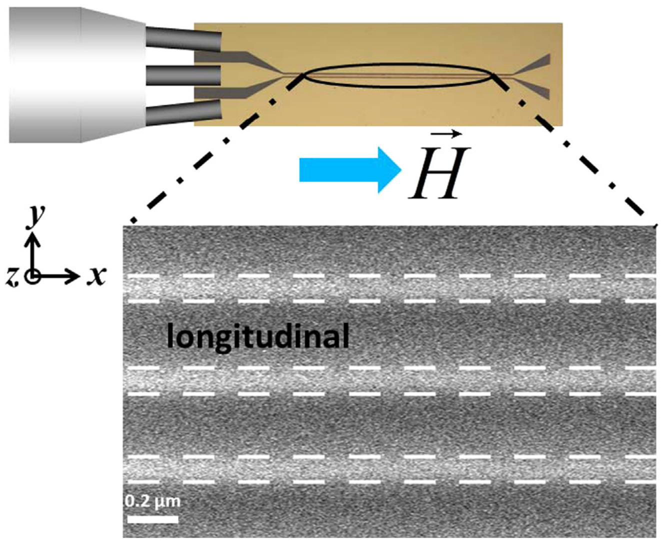

Fig. 1

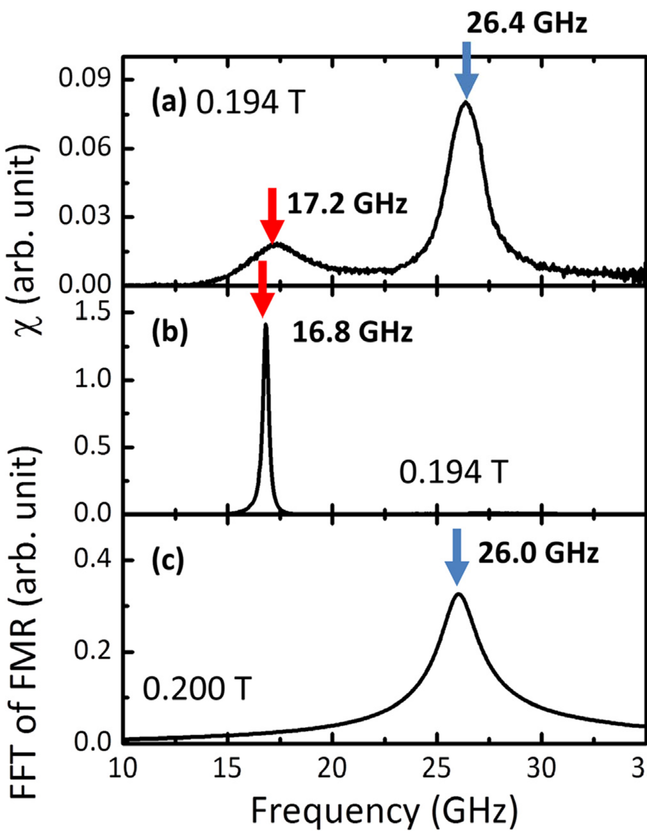

Fig. 2

direction for FMR measurement is also depicted.

We use VNA-FMR spectra to measure imaginary parts of the susceptibility of the samples [16]. The measured imaginary parts of the susceptibility raw data are calibrated with the careful calibration procedures [2]. The calibrated imaginary parts of the susceptibility are shown in Fig. 2(a) and (b) for an applied magnetic field at 0.194 T for the nanowire arrays. The un-patterned thin film is also examined for the reference. We find two resonance frequencies, 17.2 and 26.4 GHz, as shown in Fig. 2(a) for the nanowire

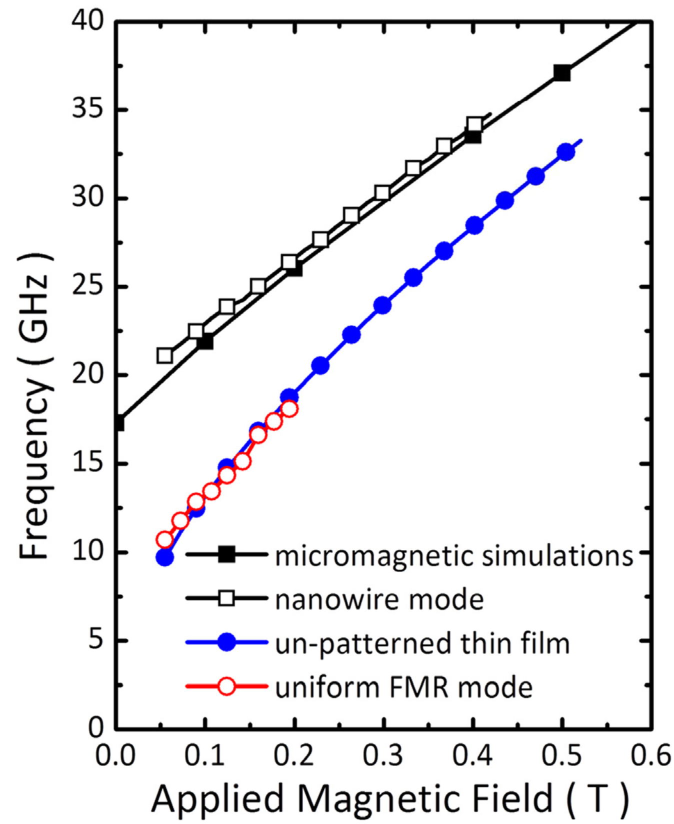

Fig. 3

array, while there is only one peak at 16.8 GHz for the un-patterned thin film as shown in Fig. 2(b). We believe that the smaller peak (17.2 GHz) in Fig. 2(a) is originated from the un-patterned part of the nanowire array, because the frequency is closed to the un-patterned thin film's peak (16.8 GHz). Probably, the un-patterned part of the nanowire is formed due to poor e-beam lithography processes. On the other hand, the resonance frequency near 26.0 GHz is calculated from micromagnetic simulation at an applied magnetic field at 0.200 T, as shown in Fig. 2(c). We clarify the source of the main peak (26.4 GHz) is nanowire arrays by using micromagnetic simulation. These two peaks named as the uniform FMR mode (smaller peak position) and nanowire mode (higher peak position).

In order to determine the saturation magnetization, the resonance frequencies are measured as a function of the applied magnetic field, and the results are fitted with the Kittel's equation [17]. This equation employs the corresponding demagnetization factors of $N_x = 0$, $N_y = 0$ and $N_z = 1$ for un-patterned film, when applied magnetic field H is x- direction with following equations,

$$f = \frac{\gamma}{2\pi}\sqrt{\left\{H + \left(N_y - N_x\right)M_s\right\}\left\{H + \left(N_z - N_x\right)M_s\right\}}. \tag{1}$$

Here, γ is the gyromagnetic ratio, H is the applied magnetic field, M_s is saturated magnetization, N_x, N_y, and N_z are the demagnetization factors applying the cyclic permutation for the applied magnetic field direction.

The micromagnetic simulations are performed by using the Objective Oriented MicroMagnetic Framework (OOMMF) [18] with 2-dimensional periodic boundary condition (PBC) [19]. We select a square slat of $100\ \text{nm} \times 100\ \text{nm} \times 30\ \text{nm}$ nanowire separated 200 nm in y- direction with a cell size of $5\ \text{nm} \times 5\ \text{nm} \times 30\ \text{nm}$. The material parameters of CoFeB used in our simulation are summarized as follows: $M_s = 15.79 \times 10^5$ A/m, the exchange