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ABSTRACT

In this work, planar symmetric (Dot) and non-symmetric (Nanowire) structures were combined to fabricate the modulated planar structures (Dumbbell) of Ni$_{80}$Fe$_{20}$. Four set of samples were fabricated on top of the signal line of coplanar waveguides with dumbbell’s axis along and perpendicular to it using methods of photolithography, electron beam lithography and liftoff. The diameter of the dots was varied to study the effect on both static and dynamic properties of modulated structures. The static magnetization reversal was investigated by NanoMOKE measurements, whereas broadband ferromagnetic resonance spectroscopy was carried out to probe the dynamic properties in GHz range. Micromagnetic simulations were performed to comprehend the experimental results in detail.

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I. INTRODUCTION

The static and dynamic properties of micron and nano-size ferromagnetic structures have been studied extensively with the motivation of applications in spintronic, magnonic, targeted drug delivery, microwave devices and more. Magnetization reversal, nucleation and propagation of domain walls, static and dynamic properties for dot and planar nanowires have also been studied in great details. Pinning of domains at modulated structure and quantify them for the purpose of magnetic memory devices was studied. Tunable frequency magnonic devices and magnonic band gap on edge modulated structure has also been discussed. In this paper, planar dumbbell shaped structures were considered to study the static and dynamic properties. The magnetization reversal process, and spin wave excitation show unique features depending on the size of the dots as well as orientation of external magnetic field with respect to structures. Broadband ferromagnetic resonance was used to collect magnetic field and microwave frequency dependence magnetization dynamic in Gigahertz frequency range. Magneto-Optic-Kerr Effect (MOKE) was used to collect the magnetic hysteresis loop (MHL) at room temperature. Both static and dynamic experimental results are corroborated with micromagnetic simulation.

II. EXPERIMENT METHODS

Ground-signal-ground (G-S-G) type Coplanar waveguides (CPWs), with 20 micrometer width signal line and 10 micrometers G-S distance, were fabricated on (100) Silicon substrate using standard photolithography process followed by the deposition of Titanium, Copper and Gold having thickness of 5, 150 and 10 nm respectively and finally liftoff. Before their fabrication, the shape and size of CPW was optimized to achieve the characteristics impedance of 50 ohm for an impedance match and lossless transmission line using CST MICROWAVE studio software. Afterward, four sets of samples were fabricated on top of CPW’s signal lines by using electron beam lithography and subsequently by the deposition of a 50nm thick Ni$_{80}$Fe$_{20}$ film using sputtering
technique. The information regarding the samples are as follows: two set of samples (D-2-PA and D-4-PA) were fabricated with the length of wires connecting the dots oriented along the CPW’s signal line (which is shown in figure 1[c]); and 2 sets of samples (D-2-PE and D-4-PE) with the dumbbells arranged perpendicular to the signal line. The wires connecting the dots have a length of 4 micron, width 500 nm and thickness of 50 nm for all samples. The diameter of dots were 2 microns for D-2-PA and D-2-PE series and 4 microns for D-4-PA and D-4-PE. The distance between dumbbells was kept larger than 2 micrometer to insure a negligible effect of the dipolar interaction between them. The systematic structure of the samples with the dumbbell pattern on top of the signal line is presented in figure 1. The measurements were performed at room temperatures so that samples might be oxidized on the surface up to few nanometers.

The static measurements were carried out using NanoMOKE applying the external magnetic field in the plane of the samples and along the CPW. Magnetic hysteresis loops (MHLs) were collected for all samples. For dynamic characterization, Vector Network Analyzer ferromagnetic resonance (VNA-FMR) technique was used to probe the FMR spectra at different fields sweeping the microwave frequency. Both static and microwave (AC) fields are oriented in the plane of the samples, with the AC field always along the width of signal line of the CPW. For each static magnetic field the microwave frequency was swept and scattering parameter ($S_{21}$) was tracked. The experiment was repeated in the field step of 5 Oe and a three-dimensional contour plot of the transmission coefficient $S_{21}$ as a function of field and frequency was constructed.

To better understand the experimental results, graphical processing unit (GPU) based Micromagnetic simulations were performed using mumax. A single dumbbell with periodic boundary conditions and a cell size of 5x5x1nm in x, y and z direction respectively was considered. The x and y orientation were in plane and z was considered out of plane. The details regarding material parameters, and the way the imaginary part of susceptibility was calculated, is well explained in our previous work.

III. RESULTS AND DISCUSSION

Experimental normalized MHLs for samples D-2-PA, D-4-PA, D-2-PE and D-4-PE are presented in figure 2. For sample D-2-PA, almost rectangular shaped MHL, having coercivity of 33 Oe, with small two kinks at unsaturated state were observed. In contrast, zero coercivity was observed for D-2-PE samples. Similarly, in case of D-4-PA, modulated MHL with prominent kinks (compared to D-2-PA) and coercivity of 15 Oe were observed. Zero coercivity with lower saturation magnetization field (compared with D-2-PE) was observed for D-4-PE. To understand these experimental MHL loops, micromagnetic simulation was performed and results are presented in figure 3. Applied external magnetic field direction with respect to the dumbbell is shown with an arrow in figure 3. In figure 3, the left panels are MHLs and right panels represent orientation of magnetization at different points of MHLs. When external magnetic field was decreased from the positive saturation point, the magnetization reversal process started from dot or wire depending on the orientation of external magnetic field with respect to samples. For D-2-PA, at point II, the vortex with opposite chirality evolved in the dots. Decreasing the magnetic field, the vortex could not pass from the notch and they move in opposite direction within dot. Important thing to notice here is that the resultant contribution of two dots were zero because of the opposite chirality of vortexes and contribution for MHL was mainly from wire. Micromagnetic simulations represent very well the experimental results. In addition, transverse type domain wall propagate along the notch and magnetization reversal takes place of wire. In case of D-2-PE, when magnetic field decrease after saturation (for region II), the diamond type pattern of magnetization appears in center of the wire and two vortexes with opposite chirality appear on each dot. On decreasing external magnetic field, two vortexes merge on single one (D-2-PE, III) and further decreasing external magnetic field, the vortex able to move from the notch and two opposite chirality vortex
merge at the center of connecting wire. Again, the resultant contribution from two dots was zero because of the opposite chirality. The low coercivity was resulted only from wire because of the shape anisotropy when external field was perpendicular to it. In case of D-4-PA, when magnetic field was decreased after saturation, two vortexes with opposite chirality are observed on each dot. Unlikely on D-2-PA, the bigger size of dot allowed the creation of a double vortex on each dot. These two dots merge on a single dot and start
FIG. 4. [A] Contour plots of experimental FMR, [B] Micromagnetic results for [A].

FIG. 5. Snapshot dynamic susceptibility at field 1KOe from micromagnetic simulation.
to move on opposite direction. The hysteresis loop was mainly contributed from the wire because of the net resultant of magnetization from dots are cancel out because of the opposite chirality of vortex. The magnetization reversal process of D-4-PE is similar compare to the D-2-PE.

In case of dynamic study, the three-dimensional contour plots of the scattering parameter ($S_{21}$) for experimental and micromagnetic simulations are presented in figure 4[A] and [B], respectively. Two resonance modes were observed for all four set of samples. However, the amplitude of absorption intensity as well as the gap between the two resonance frequencies varied. In the case of D-2-PA and D-4-PA, the gap between the two resonance frequencies is 1GHz. However, in case of D-2-PE and D-4-PE, the gap in resonance frequencies is lower and merge on a single resonance mode with a large linewidth, especially at higher frequencies. The snapshot of the spatial distribution of dynamic susceptibility, at magnetic field 1kOe, were extracted at resonance frequencies and presented in figure 3 to understand the experimental results. For D-2-PA and D-4-PA, first and second resonance modes were contributed from dot and wire respectively. Different shape anisotropies of dot and wire, presence of notch between them thwart the uniform excitation of magnetization at single frequency. In case of D-2-PE, the first mode is an edge mode from both dot and wire. The magnetostatic field at edges of wire and dot allows to excite the magnetization at lower frequency in this configuration, however it was not possible to detect experimentally because of smaller amplitude compare to bulk modes. Mode II was contributed from the wire and III mode was from all around the sample. These bulk modes are dominated by the exchange coupling of spins and they excite relative higher frequency compared to the edge mode. Similar contribution was observed for D-4-PE with negligible contribution from edge mode. The magnetostatic field, shape anisotropy plays significant role for the excitation and propagation of magnetization especially for modulated structures.6,25 The amplitude of resonance was simply dependent on the volume of structures.

In conclusion, static and dynamic properties in dumbbell structures were studied by modulating the physical structures in a controlled manner. The notch on dumbbell does not allow to move domain freely from dot to wire. Evolution of domains, chirality of vortexes and their depend on the size of the dot as well on the direction of applied field with respect to the structures. This study will help to design domain wall-based devices. In case of dynamic response, the wire and dot excite at different frequencies even the samples were in magnetically saturated states. Whenexternal field was along wires, dot was excited at lower frequency and wire at higher frequency. However, the reverse response appears when external field was perpendicular to wires. These tuning properties can be implemented to design reconfigurable multiband microwave filters as well as magnonic devices.

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