구두발표 I-2

Ferromagnetic Resonance in Multi-Ferroic Thin Films Comprised of Nickel Ferrite Nano-Pillars in a Bismuth Iron Oxide Matrix

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Multi-ferroic thin films with ferromagnetic nano-pillars embedded in a ferroelectric matrix are attractive both for fundamental magnetic materials research and for a wide variety of magneto-electric high frequency nano-device applications [1]. Up to now, most of the work on such systems has focused on quasi-static magneto-electric effects. There has been little work on the dynamic response, ferromagnetic resonance (FMR), or connections between the FMR response and film structure.

This paper reports first time FMR data on such multi-ferroic films. The two samples used in this work were comprised of nickel ferrite nano-pillars in a bismuth iron oxide matrix with different film thickness and pillar height (h) to diameter (d) aspect ratios. For both samples, the nominal pillar diameters were about 80 nm. The measurements were done at 9.45 GHz for the full range of the static field angle (Θ_H) relative to the film plane. For the low aspect ratio (LAR) pillar sample with $h/d \sim 1.5$ and a magnetic volume fraction f of about 36%, the data on the FMR field H_r as a function of Θ_H indicate a collective dynamic response consistent with thin film geometry. This sample also showed evidence of classic standing spin wave resonance (SWR) for fields aligned within 20 of perpendicular. For the high aspect ratio (HAR) pillar sample with $h/d \sim 5$ and a magnetic volume of about 17%, the response is more consistent with isolated pillar FMR. This sample showed no spin wave resonance signature.

Figure 1 shows representative data on the FMR field H_r vs. Θ_H for both samples. Note that $\Theta_H = 0$ corresponds to a static field directed parallel to the film plane and perpendicular to the axis of pillars, while $\Theta_H = \pm 90$ correspond to a static field directed perpendicular to the film plane and parallel to the pillar axis. The solid curves in (a) and (b) show fits based on the assumption of a continuous thin magnetic film and non-interacting magnetic pillars, respectively. For the LAR pillar film results in (a), the FMR field decreases as the static field angle goes from out-of-plane to in-plane and shows a nominal minimum at $\Theta_H = 0$. The fitted curve is based on the effective saturation induction $f4\pi M_s - H_u$ of 850 Oe. Here, $4\pi M_s$ denotes the saturation induction of the pure nickel ferrite and H_u denotes a possible uniaxial anisotropy field for an easy axis along the pillar axis and perpendicular to the film plane. For the HAR pillar film results in (b), the FMR field increases as the static field goes from out-of-plane to in-plane and is maximum at $\Theta_H = 0$. Here, the fitted curve is based the resonance condition for non-interacting pillars with the specified aspect ratio, the $4\pi M_s$ for nickel ferrite, and an additional uniaxial anisotropy field along the pillar axis of 1600 Oe.

Figure 2 shows representative spin wave resonance results for the LAR sample θ_H at = 90°. Graph (a) shows a plot of the derivative of absorbed power as a function of the static field *H*. The main trace shows main FMR peak at *H* = 4460 Oe. The expanded trace shows three additional resonance peaks below the main FMR that correspond to spin wave resonance standing modes. The index *n* denotes the inferred standing wave mode number for the peaks in the spectrum, as indicated. This index corresponds to the number of standing mode half wavelengths across the film thickness. Graphs (b) and (c) show the resonance field for the indicated modes, designated as H_n, and the half power mode linewidth ΔH_n as a function of square of the mode index *n*, respectively. The solid circles show the data. The solid straight line in (a) shows a linear fit to the data based on the Kittel SWR theory. The slope yields a value of the exchange stiffness constant A of 1.0×10^{-6} erg/cm, in the same range as found for a wide variety of isotropic magnetic systems. Based on the thickness variation thin film model of Saraf *et al.* [2], the slope of the linewidth fit in (c) indicates a thickness variation of about 20%.

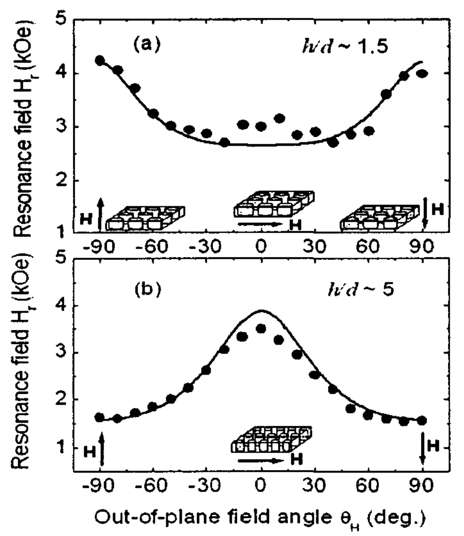

FIG. 1. Ferromagnetic resonance field H_r as a function of the field angle θ_H for (a) the LAR pillar sample with *h/d* ~ 1.5 and (b) the HAR pillar sample with *h/d* ~ 5. The continuous solid curves show fits to the data.

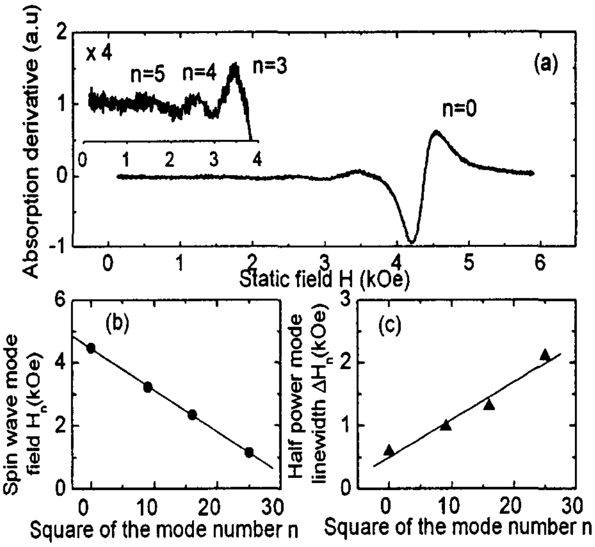

FIG. 2. (a) Absorption derivative vs. field spectrum for the LAR sample with *h/d* ~ 1.5 with the static field *H* perpendicular to the film plane. Graphs (b) and (c) show the resonance field for the modes, H_n, and the mode linewidth ΔH_n as a function of square of the mode number *n*, respectively.

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