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2019

He, S., Qin, Q., Zhou, T., & Panagopoulos, C. (2019). Angle-resolved broadband ferromagnetic resonance apparatus enabled through a spring-loaded sample mounting manipulator. *Review of Scientific Instruments*, 90(7), 076103-. doi:10.1063/1.5113773

<https://hdl.handle.net/10356/106823>

<https://doi.org/10.1063/1.5113773>

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Cite as: Rev. Sci. Instrum. 90, 076103 (2019); doi: 10.1063/1.5113773

Submitted: 7 June 2019 • Accepted: 10 June 2019 •

Published Online: 2 July 2019

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ABSTRACT

Broadband ferromagnetic resonance is a useful technique to determine the magnetic anisotropy and study the magnetization dynamics of magnetic thin films. We report a spring-loaded sample loading manipulator for reliable sample mounting and rotation. The manipulator enables maximum signal, enhances system stability, and is particularly useful for fully automated in-plane-field angle-resolved measurements. This angle-resolved broadband ferromagnetic resonance apparatus provides a viable method to study anisotropic damping and weak magnetic anisotropies, both vital for fundamental research and applications.

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Manipulating magnetization through electrical currents via spin-transfer torque and spin-orbit torque is superior to conventional schemes such as the usage of magnetic fields due to its scalability and energy efficiency.¹ Consequently, emerging applications including spin-transfer-torque magnetic random access memory have attracted considerable attention.^{2,3} Magnetic thin films and multilayers with low damping constant and high anisotropy are essential for reducing the switching current density without sacrificing data retention performance.

Broadband ferromagnetic resonance (FMR) is widely used for studying the mechanism of magnetization relaxation in ultrathin films.^{4,5} It has been shown that the damping parameter can be determined accurately in a field perpendicular to the plane geometry,^{6,7} assuming that damping is isotropic. However, both phenomenological theory and recent experiments indicate that the Gilbert damping constant can depend on the orientation of the magnetization vector.^{8,9} Crucially, prior to the calculation of anisotropy in damping, it is important to determine the extrinsic contributions to the FMR linewidth such as inhomogeneous broadening

and magnetic anisotropy;^{7,10} therefore, it is desirable to develop an angle-resolved broadband FMR apparatus to measure spectra at various magnetization orientations and frequencies. Note that commercial EPR systems have angle-resolution but can only work at a given frequency, thus being not ideal for studying anisotropy in damping.

Here, we present a fully automated angle-resolved broadband FMR apparatus enabled by a spring-loaded in-plane sample mounting manipulator. In the broadband FMR technique, the thin film sample is flipped and placed on top of a coplanar waveguide (CPW). The gap between the film and the CPW is minimized to ensure that a uniform in-plane microwave field (h_{rf}) is applied on the sample under investigation. Because the precession of magnetization is caused by the component of h_{rf} perpendicular to the external field H_{dc} , the amplitude of the FMR signal varies with the orientation of H_{dc} and vanishes if $H_{dc} \parallel h_{rf}$ in a conventional rotating field design. Hence, it is preferred to rotate the sample while keeping the waveguide (direction of h_{rf}) and the direction of H_{dc} fixed. However, it is necessary to decouple the contact between the sample and the CPW

FIG. 1. Steps of sample rotation scheme. (a) Initial configuration, (b) lift the sample up to create a gap between the sample and CPW, (c) rotate the sample to the desired orientation, and (d) reload the sample.

before each sample rotation in order to avoid scratching the sample and the CPW (Fig. 1). Here, we developed an in-plane sample mounting manipulator to meet stringent requirements of the FMR technique while incorporating angle-resolution.

As shown in Fig. 2(a), the axis of the in-plane sample mounting manipulator is aligned to the center of the FMR probe head where a CPW is mounted. The FMR probe head [Fig. 2(b)] is attached to a

separate supporting rod, the axis of which is perpendicular to the in-plane sample mounting manipulator. The manipulator is attached to a rotary positioner, which controls the sample orientation. The rotary positioner, in turn, is put into a linear positioner to control the height of the manipulator and hence the location of the sample.

The in-plane rotation procedure is as follows: First, attach the sample [item 11 of Fig. 2(d)] to the bottom of the sample holder using glue or double-sided tape. Then, mount the sample holder to the manipulator just as mounting a screw. Next, the software will follow the procedure listed in Figs. 1(a)–1(d) to measure FMR spectra at specified in-plane field orientations. Most importantly, to avoid damaging the CPW and the sample, the sample holder height is controlled by a Cu spring [item 5 of Fig. 2(d)] and two slots [item 3 of Fig. 2(d)]. The usage of the spring minimizes the gap between the sample and the CPW with a controllable force [Fig. 2(a)], which is essential for the reliability of this manipulator. The tolerance of the travel distance is about 5 mm, which is orders magnitude larger than the control precision of commercially available linear positioners.

Shown in Fig. 3 are the in-plane FMR data obtained for a 10 nm Py sample prepared by magneto-sputtering. Resonance line shape is observed for all of the field/magnetization orientations. The nearly isotropic FMR response is shown in Fig. 3(a). We fit the data to a Lorentz line shape,

$$S_{21} = \frac{A \cdot (\Delta H/2)^2 + B \cdot \Delta H/2 \cdot (H - H_{Res})}{[(H - H_{Res})^2 + (\Delta H/2)^2]} + C, \quad (1)$$

where A and B are the amplitude of symmetric and antisymmetric terms, respectively, C is the background of the spectrum, H_{Res}

FIG. 2. (a) A schematic of the FMR head and sample location during in-plane rotation. (b) The FMR probe head. (1) Copper housing; (2) End Launch connector; (3) coplanar waveguide (CPW); (4) 2.4 mm cable connection port; (5) BeCu spring clip; (6) clip base; (7) Cu spring. (c) The angle-resolved FMR system based on an electromagnet. (d) The in-plane sample mounting manipulator. (1) sample holder; (2) spring holder; (3) set screw; (4) housing tube; (5) Cu spring; (6) shaft; (7) adapter to the positioner; (8) screw hole for item 3; (9) guiding slot; (10) mounting screw hole; (11) sample.

FIG. 3. Results of a Si/Py 10 nm/Ta 5 nm sample. (a) 2D mapping of the FMR spectra at 10 GHz. (b) The field orientation ϕ_H dependence of the resonance field. (c) The FMR linewidth vs field orientation ϕ_H . (d) The effective saturation magnetization and anisotropy field value calculated at various frequencies.

is the resonance field, and ΔH is the full width at half maximum. We find a weak two-fold symmetry in the magnetization dependence of H_{res} [Fig. 3(b)] and therefore determine the resonance condition by adding a uniaxial anisotropy term in the total energy and solving the Smit-Beljers equation,¹¹

$$2\pi f = \gamma \sqrt{H_{\text{res}} \cos(\varphi_M - \varphi_H) + 4\pi M_{\text{eff}} + H_{\text{uni}} \cos^2 \varphi_M} \times \sqrt{H_{\text{res}} \cos(\varphi_M - \varphi_H) + H_{\text{uni}} \cos 2\varphi_M}. \quad (2)$$

Notably, $4\pi M_{\text{eff}}$ and H_{uni} are material related parameters and do not change with measurement frequency. As shown in Fig. 3(d), the values determined are nearly identical for all the frequencies used. Remarkably, the small anisotropy, which is less than 3 Oe, can be determined with a standard deviation of less than 5%. The FMR linewidth at a given frequency is also essentially the same for all magnetization orientations, as expected by the isotropic nature of the Py film [Fig. 3(c)].

In summary, we developed a spring-loaded sample loading manipulator for reliable and fast angle-resolved broadband FMR measurements. We demonstrated the suitability of the apparatus for determining the magnetic anisotropy with high precision at all in-plane magnetization orientations. Importantly, such a manipulator can be designed in a variety of configurations to meet the geometrical constraints of a particular system.

C.P. acknowledges support from the National Research Foundation (NRF), NRF-Investigatorship (No. NRFNRFI2015-04).

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