

Tunable resonant properties of perpendicular anisotropy [Co/Pd]/Fe/[Co/Pd] multilayers

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We describe the static and dynamic magnetic behaviors of Fe films (thicknesses 2, 4, and 6 nm) sandwiched between Co/Pd multilayers with strong perpendicular magnetic anisotropy. Out-of-plane measurements of both magnetization and ferromagnetic resonance confirm well-defined Fe layer response modified by large perpendicular exchange field arising from the coupling with the Co/Pd. The field/frequency dispersion is linear for all samples with field intercepts increasing with Fe layer thickness. Analysis in terms of shape anisotropy and interfacial exchange model yields a large out-of-plane interfacial coupling of $\sim 3.0\text{--}3.7$ erg/cm² that is mediated by the coupling across thin Pd layers. The value of this interface exchange is also shown to be tunable with interfacial Pd thickness.

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INTRODUCTION

Exchange-spring structures, the coupling of hard (or, more generally, high anisotropy) materials and soft materials, are being pursued for applications such as permanent magnet,^{1,2} magnetic recording, magnetic memories, and high frequency materials to name a few.^{4–13} By coupling the soft to the hard layer, it possible to tune both the static and dynamic responses of the soft layer and derive new functionality. Such coupling can be applied to enhance properties in perpendicular magnetic recording media,^{3,4} as well as tuning the reversal properties in high-density bit patterned media^{5–10} and can be further optimized for microwave assisted magnetic recording.¹¹ The exchange coupling of the soft layer to the hard layer is also being pursued as a pathway for raising the resonant frequency of the soft layer¹² and the operating frequencies of planar microwave devices.¹³ When the soft layer is either pinned or exchange-coupled at the interface of the hard layer, there are significant shifts in the resonance frequency, with only a small reduction in the strength of the resonance. Such coupled structures are also being pursued in spin-torque devices. In many spin-torque oscillator designs, an external magnetic field is required.¹⁴ For the practical use, the field could be eliminated by utilizing a large effective magnetic field that is applied to the free layer by indirect exchange coupling to a high anisotropy layer.¹⁵ Exploiting the resonant properties of the soft layer in an exchange coupled composite can lower the current required for spin-torque switching.¹⁶

In all these applications, the functionality arises from interfacial coupling where the properties are tuned by adjusting the constituent materials, their relative thickness, and the strength of the interfacial coupling. For many of applications, it is important to maintain the well-defined resonant properties of the soft layer. Recent studies have found a positive correlation between the magnetic damping parameter α

and the anisotropy (K_U) of the layer.^{17–22} By using a composite structure, it may be possible to exploit both the low damping and high moment of the soft layer and high anisotropy of the hard layer in ways not possible in a single material. In this paper, we report static and dynamic results in continuous films of a soft Fe layer coupling to hard Co/Pd layers, producing a significant out-of-plane exchange field acting on the Fe layer that can be further adjusted by the thickness of the Fe and Pd layers.

EXPERIMENTAL DETAILS

The multilayer films for this investigation are Ta(4)/Pd(4)[Co(0.3)/Pd(0.7)]_{×5} Fe(X_–)/Pd(0.7)[Co(0.3)/Pd(0.7)]_{×5} Ta(4), where the thicknesses are in nm and X = 2, 4, or 6 nm. An additional sample was prepared with 0.9-nm Pd layers at the 2-nm Fe interfaces as follows: Ta(4)/Pd(4)[Co(0.3)/Pd(0.7)]_{×4}/Co(0.3)/Pd(0.9)/Fe(X)/Pd(0.9)[Co(0.3)/Pd(0.7)]_{×5} Ta(4). The samples were grown by dc magnetron sputtering at 3-mTorr Ar pressure onto ambient temperature SiO_x coated Si wafers. This result in (111) crystallographic texture and strong perpendicular magnetic anisotropy. Similarly grown Co/Pd multilayers have perpendicular anisotropy fields on the order of 20 kOe.

The static magnetic properties were studied both by polar magneto-optical Kerr effect (MOKE) and vibrating sample magnetometry. Dynamic measurements were done by ferromagnetic resonance (FMR). FMR measurements were made at room temperature on a broadband co-planar waveguide with field applied normal to the film plane at frequencies ranging from 2 to 16 GHz. Field modulation results in a derivative absorption line-shape. In this configuration, neglecting in-plane anisotropy, the resonance field will be given by

$$H_{res} = \frac{\omega}{\gamma} + 4\pi M_s - H_{ex}, \quad (1)$$

where ω is the microwave radial frequency, γ is the gyromagnetic ratio, $4\pi M_s$ where M_s is the saturation

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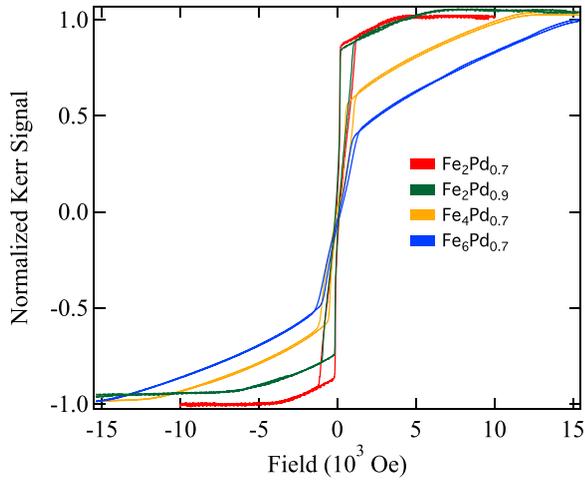


FIG. 1. MOKE out-of-plane magnetization curves for each of the samples reported. Higher saturation fields are observed for larger Fe layer thicknesses.

magnetization for the Fe layer is the thin-film shape and H_{ex} is the effective field acting on the Fe layer that arises from the ferromagnetic coupling of the Fe to the Co/Pd multilayer. Equation (1) assumes that the FMR signal is dominated by the Fe layer. This is not unreasonable as the expected resonance frequency for the Co/Pd layers is >50 GHz.

RESULTS AND DISCUSSION

Out-of-plane magnetization measurements are shown in Fig. 1. The loops show a two-phase behavior. There is a low field hysteretic region that reflects the reversal of the Co/Pd layers where the shape of the hysteretic region is consistent with the reversal via the formation of stripe domains. For higher field, there is gradual increase toward saturation which reflects the rotation of the Fe layer. In the absence of any coupling to the Co/Pd layers, one would expect the Fe layers to be dominated by its internal demagnetizing field and saturate at $4\pi M_s$. For bulk Fe, this corresponds to 21 kOe. For the present films, the saturation field is well below this value and decreases with decreasing Fe thickness indicating the coupling between the Fe and [Co/Pd] layers providing an effective field acting on the Fe layers. This field

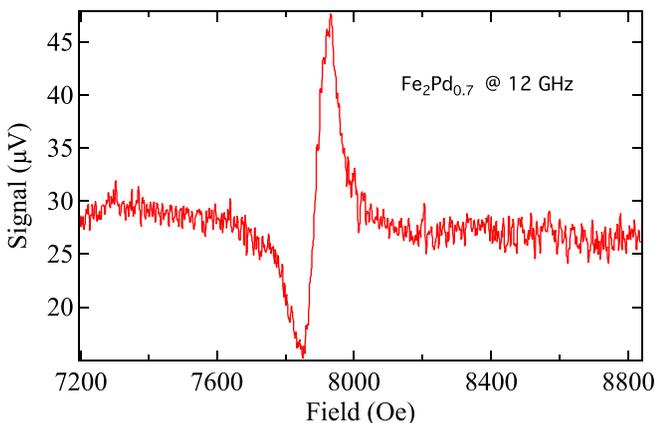


FIG. 2. FMR spectrum for $\text{Fe}_2\text{Pd}_{0.7}$ sample at 12 GHz. As a derivative signal, the resonance field is midway between the signal external points. The signal-to-noise and line width are typical for all spectra utilized in this study.

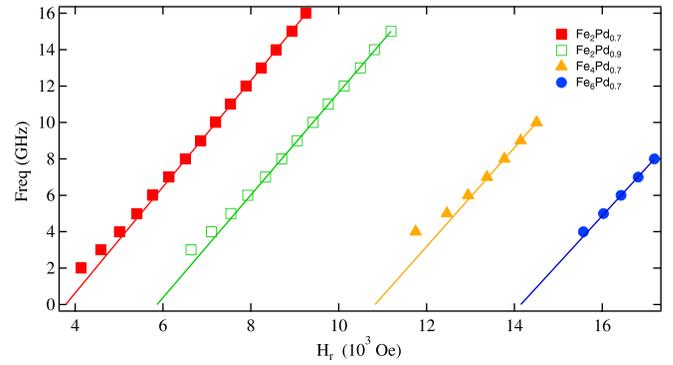


FIG. 3. Frequency/field dispersion, following Eq. (1), for the samples measured. Near linear behavior with dramatically different field intercepts indicates large and systematic variations in out-of-plane anisotropy. Lines are fits to data well above Fe saturation fields for each sample.

can be estimated by the difference between the measured saturation field and the expected shape anisotropy (21 kOe).

However, to get a more quantitative measure of the Fe layer properties, we used FMR. Figure 2 shows a FMR spectrum typical in this study, with good signal-to-noise and well-defined, derivative line shape. Both the line position and shape are consistent the FMR resonance arising predominantly from the Fe layer.²³ As state above, the Co/Pd resonance is expected at much higher frequencies. We first focus on the resonance position—an indicator of the internal anisotropy fields—and then discuss the line widths.

As seen in Fig. 3, resonant fields varied nearly linearly, with frequency for the four samples when measured above the saturation field. There is a slight deviation from linearity when the applied field approaches the saturation field where the Fe layer is no longer aligned with the applied field that is assumed in Eq. (1). All slopes are consistent with that from a well-defined Fe resonance (approximately 2.9 GHz/kOe). For an isolated Fe layer, the expected zero frequency intercept will be the shape anisotropy field ($4\pi M_s$). However, the field intercepts decreases dramatically with decreasing Fe thickness, the values of which are shown in Table I. The lower field intercepts for the thinner Fe layers indicates the presence of an out-of-plane effective field (H_{ex}) arising from the interfacial coupling that is counteracting the shape anisotropy.

One may apply a simple model to the Fe layer for the purpose of determining the interface exchange energy. In this model, one assumes that H_{ex} arises from the exchange coupling at each Fe interface, formulated as follows:

$$4\pi M_s - H_{ex} = \frac{2J_{exchange}}{M_s d_{Fe}}. \quad (2)$$

Assuming bulk Fe M_s , one obtains rather large, out-of-plane exchange energies for each of the samples as indicated

TABLE I. Linear fit parameters from the frequency/field dispersion data.

Sample	Slope (GHz/kOe)	Intercept (G)	J_{exch} (erg/cm ²)
$d_{Fe} = 2$ nm	2.91	3760	3.0
$d_{Fe} = 4$ nm	2.65	10 700	3.6
$d_{Fe} = 6$ nm	2.63	14 100	3.7
$d_{Fe} = 2$ nm + Pd _{0.9}	2.82	5870	2.3

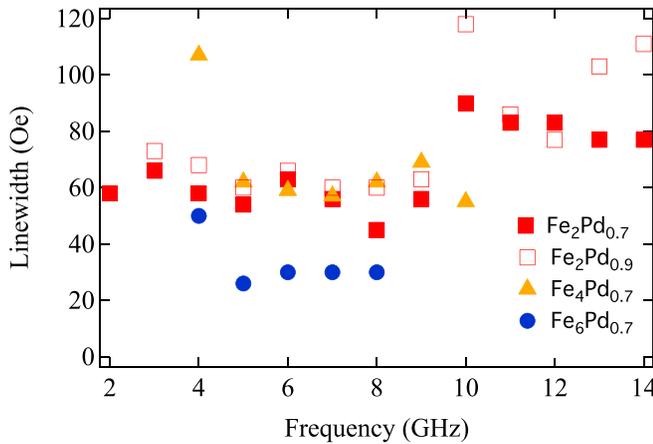


FIG. 4. Resonance line width data for the four samples reported.

in Table I. The strong ferromagnetic coupling across the Fe layer is consistent with the properties of Pd which is nearly ferromagnetic with an anomalously large susceptibility. The results in the Pd atoms at the Fe/Pd interface being strongly polarized by the Fe atoms. This polarization has been observed as enhanced magnetic moments and strong ferromagnetic interlayer coupling for Pd thicknesses of 4 monolayers or less.²⁴ Note that from Fig. 3 and Table I modifying the Pd thickness adjacent to the Fe provides additional tunability to the interfacial exchange. The values for the coupling of across the 0.7-nm Pd layer are consistent with the previous studies of domain wall states in Co/Pd multilayers.²⁵

While the interfacial coupling to the Co/Pd layers provides a large effective field acting on the Fe layer (>10 kOe for a 2-nm Fe film), the Fe resonance line width is not significantly affected. FMR line widths for these samples are shown in Fig. 4. The values, ranging from 30 Oe in the thickest Fe films to less than 120 Oe in the thinner Fe, indicate high quality Fe layers, consistent with that observed in epitaxial Fe on BaTiO₃,²⁶ on GaAs (Ref. 27) and even Fe grown on single crystal Cu.²⁸

Above 4 GHz, there exists a general positive slope in the line width data. For lower frequencies, incoherent behavior in the Fe layer may result in additional broadening of the line width. The linear behavior at higher frequencies is consistent with contributions from damping (slope) and magnetic inhomogeneities (ΔH_0)²⁹ according to

$$\Delta H = \Delta H_0 + 1.16\alpha \frac{2\pi f}{\gamma}, \quad (3)$$

where α is the intrinsic damping parameter and f is the resonance frequency. While the scatter in the data prevents precise determination of these parameters, the inhomogeneous contribution is in the range of 45 to 60 Oe and the slope is less than 4 Oe/GHz suggesting an upper limit of 0.01 for the damping parameter, α .

CONCLUSION

We have investigated the anisotropy and resonant properties in continuous films of Fe coupled to magnetically hard

Co/Pd layers using magnetization and FMR techniques. By examining samples of varying Fe thickness, we were able to extract the interface exchange, which is large due to the strong coupling across Pd and out-of-plane as a result of the perpendicular magnetic anisotropy of the Co/Pd multilayers. In addition, we determined this interface contribution to be tunable by manipulating the Pd interface thicknesses. This highlights the ability to tune the resonant property of soft layer by coupling to a hard layer with controlled anisotropy.

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