Perpendicular Magnetic Anisotropy in CoFeB/Pd Bilayers

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Perpendicular magnetic anisotropy is observed in ultrathin (~ 0.6 nm) amorphous $Co_{40}Fe_{40}B_{20}$ when sputtered on an MgO (001) buffer layer and capped with Pd. The layers are superparamagnetic with a blocking temperature of ~ 230 K, below which they show an exponential temperature dependence of coercivity. Perpendicular magnetic anisotropy is observed in the as-deposited state and the mechanism is different from that of CoFeB/Pt, which requires postannealing. These ultrathin layers could be a model system for studies of electric field effects on magnetic anisotropy.

Index Terms—**Perpendicular magnetic anisotropy (PMA), thin-film capacitors.**

I. INTRODUCTION

RECENTLY, there has been intense interest in ultrathin films with perpendicular magnetic anisotropy (PMA) to reduce the critical current density j_c for spin transfer torque (STT) switching [1] and to study the effect of an electric field on magnetic anisotropy [2]. In spin-valve devices, such as giant magnetoresistance (GMR) or tunneling magnetoresistance (TMR) nanopillars, the use of electrodes exhibiting PMA can increase the spin transfer torque efficiency and, hence, reduce j_c [3].

PMA can be easily detected in bilayer systems by magneto-optical Kerr effect (MOKE) and extraordinary Hall effect (EHE). Bilayer films are also ideal systems for studying the electric-field control of magnetic properties [2], [4], [5]. Another advantage is the fact that the exhibited PMA is very sensitive to layer thickness and sample structure. Weisheit *et al.* demonstrated a change in the coercivities of FePt and FePd $L1_0$-ordered alloys upon application of an electric field in an electrolytic capacitor [2]. Maruyama *et al.* have demonstrated a $\sim 40\%$ change in magnetocrystalline anisotropy in epitaxial ultrathin Fe(001) [4], and more recently, electric-field-assisted magnetization reversal in FeCo layers [5]. In both cases, the electric field was applied across a micron-thick polyimide layer. The effect originates from the fact that the filling of $3d$ orbitals in the ferromagnetic layer is affected by the application of an electric field [4]. So far, the modification of anisotropy has only been investigated by MOKE.

For an electric field to have a measureable effect on the magnetization of a ferromagnetic metal, the ferromagnetic layer should be only a few monolayers thick due to the screening effect of conduction electrons. PMA layers are good candidates for electric-field effect studies since the anisotropy is realized for layers that are only a few monolayers thick. Most bilayers exhibiting PMA require a sufficiently thick metallic seed layer. Examples of these systems include Co/Pt and Co/Pd multilayers [6], [7]. In order to build a capacitor structure for the study of the electric-field modification of anisotropy, the ferromagnetic layer must be deposited on top of or beneath an insulating layer. In the normal case of a Pt/Co/Pt (or Pd/Co/Pd) sandwich, both Pt (Pd) layers induce a strong interfacial anisotropy which serves to rotate and stabilize the magnetization of the Co layer out of plane. It is generally agreed that this is due to magnetocrystalline and magnetoelastic anisotropies at the Co/Pt and Co/Pd interfaces [8], [9]. The requirement for a solid-state capacitor structure is that one metal interface must be replaced with an insulator, such as MgO or AlO_x. These layers do not induce a strong interfacial anisotropy, like Pt or Pd, in the as-deposited state. Nevertheless, Nistor *et al.* recently demonstrated that it is possible to stabilize PMA in thin layers of CoFeB grown on a buffer layer of MgO capped by Pt after annealing at 350 °C [10]. It has also been shown that with high temperature annealing, it is possible to stabilize PMA with AlO_x underlayers and this is attributed to the hybridization of the Co and O orbitals after high-temperature annealing [11].

In previous studies, it has also been shown that CoFeB layers grown on MgO with thicknesses below 1 nm are superparamagnetic [12], [13]. Ultrathin polycrystalline metallic layers can form islands on a surface if the roughness and surface wetting are not optimal, which can increase the minimum thickness required for a continuous film. However, amorphous alloys, such as CoFeB, can form continuous layers at smaller thicknesses.

Here, we present results on an ultrathin layer (0.6 nm) of amorphous CoFeB exhibiting PMA on an MgO buffer in the as-deposited state when capped with Pd. This system offers an opportunity to study changes in magnetic anisotropy under the application of an electric field by using EHE.

II. EXPERIMENTAL METHOD

Multilayer samples were grown with the following structure: $Si/SiO_2/underlayer/FM/cap$. The underlayers used were Ta 5/Pd 5 and MgO 1.4 (thicknesses in nanometers). FM layers were Co and $Co_{40}Fe_{40}B_{20}$. Cap layers were Pd and Pt.

All samples were deposited on 1″ square thermally oxidized Si(100) wafers using a fully automated SFI Shamrock deposition tool. Samples were processed without breaking vacuum. CoFeB, Pt, Pd, and Ta were dc-sputtered at an Ar pressure of 3 mTorr in a chamber with a base pressure of less than 2×10^{-7} Torr. MgO was deposited by radio-frequency sputtering using argon in a target-facing-target configuration at a pressure of 4 mTorr in a chamber with a base pressure of less than 1×10^{-8} Torr.

Magnetization measurements were performed in a Quantum Design Superconducting Quantum Interference Device (SQUID) magnetometer. Low-temperature measurements
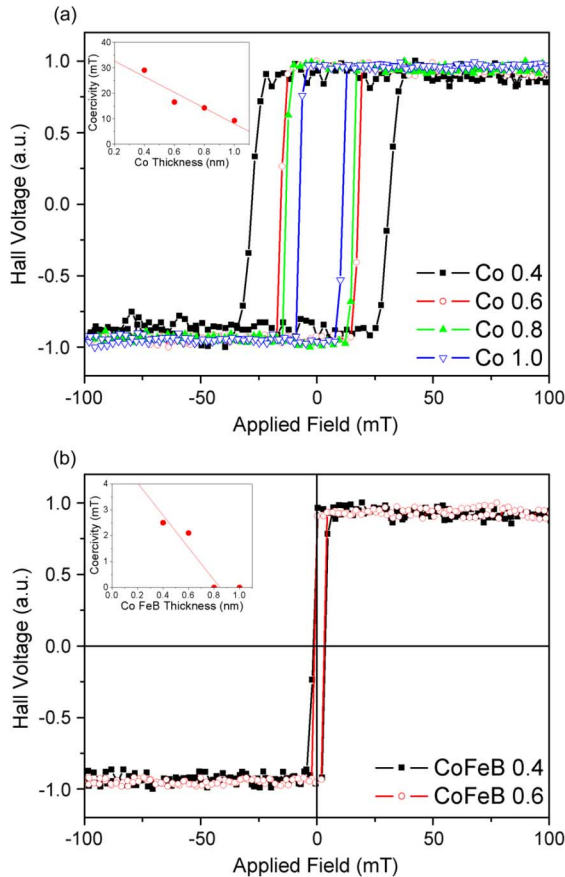
Fig. 1. FM layer thickness dependence for Ta/Pd/FM/Pd sandwiches for (a) Co and (b) CoFeB. Insets: coercivity as a function of FM layer thickness.
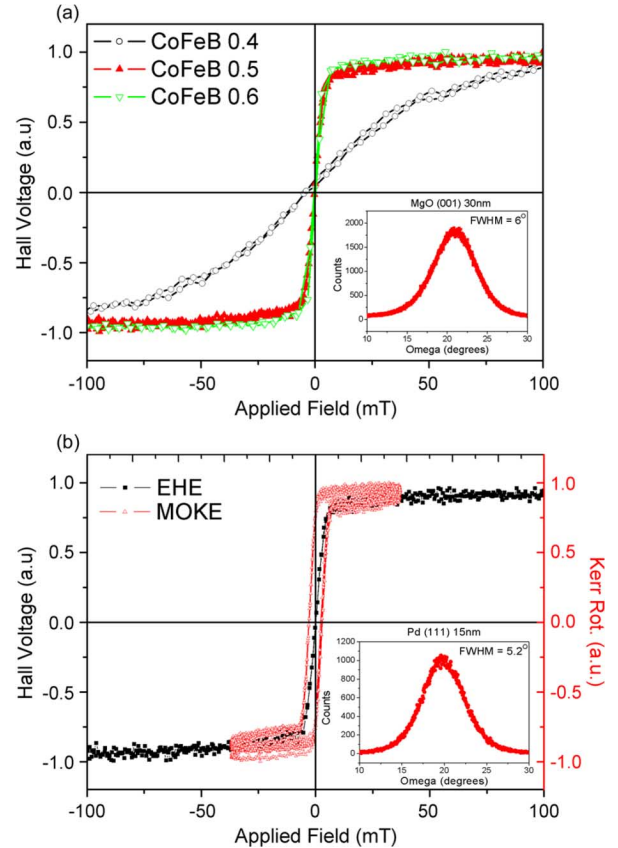

Fig. 2. (a) EHE response of MgO 1.4/CoFeB/Pd 5 as the thickness of CoFeB is varied. Inset: rocking curve for thick (30 nm) MgO underlayer. (b) MOKE and EHE loop comparison for MgO 1.4/CoFeB 0.6/Pd 5. Inset: rocking curve for the thick (15 nm) Pd capping layer.

were carried out in a cryostat with a base temperature of 13 K within an electromagnet capable of generating fields up to 180 mT. X-ray diffraction was carried out in a Philips X'Pert Pro diffractometer with an X'Celerator module.

III. RESULTS AND DISCUSSION

We first investigated the perpendicular magnetic anisotropy in Pd/Co/Pd and Pd/CoFeB/Pd sandwiches at room temperature. As the CoFeB alloy contains 20% boron, the alloy is expected to be amorphous regardless of substrate (in this case, Pd) [14].

The results are shown in Fig. 1. The coercivity decreases with magnetic layer thickness, which is consistent with the competition between the volume anisotropy term, K_v and the surface anisotropy term K_s. In the case of Co, the PMA exists up to a Co thickness of 1.0 nm, but in the case of CoFeB, both H_c and the thickness range of PMA are reduced. For the thinnest magnetic layers (0.4 nm), H_c is 40 mT in the case of Co and 4 mT in the case of CoFeB. The order of magnitude difference is similar to [10].

After investigating the PMA in the Pd/CoFeB/Pd system, we replaced the Ta/Pd underlayer with MgO. In the following structure $\mathrm{Si/SiO_2/MgO/CoFeB/Pd}$, we varied the CoFeB thickness and examined the EHE response. We also investigated the crystal structure of the MgO and Pd layers.

Fig. 2(a) shows the EHE response as a function of CoFeB layer thickness. At 0.5 and 0.6 nm, we see a vertical jump around zero field in the EHE measurements, indicative of a perpendicular easy axis of magnetization. At 0.4 and 0.7 nm, we observe

a linear EHE response. Since the coercivity is zero for all thicknesses and there is no remanence, we think the CoFeB layer to be superparamagnetic on MgO at all thicknesses investigated [15]. Fig. 2(b) shows EHE and Kerr loops for the 0.6-nm film. The MOKE loop shows coercivity, implying that the magnetization is blocked on the $\sim$ ms time scale. The full EHE loop by comparison takes several minutes to complete.

To investigate the crystal structure of MgO, we grew samples with a thick underlayer (30 nm) for XRD measurements. A weak (001) texture was observed from the rocking curve (we deposited the same CoFeB/Pd structure on top and found no qualitative difference in EHE response between the differing MgO thicknesses) see Fig. 2(a) inset. From the rocking curve FWHM data, using Scherrer's formula, we calculate the average (001) grain size to be 9.6 nm. The (001) texture of MgO implies that the CoFeB layer grows amorphous as seen in the case of MgO magnetic tunnel junctions [16]. Similarly, to investigate the crystal structure of the Pd layer, we deposited a sample with a thick Pd layer (15 nm) on top of the MgO 1.4/CoFeB 0.6 structure and examined it by XRD. A (111) texture was observed from the rocking curve which is consistent with the appearance of PMA in the system, see Fig. 2(b) inset. As in the case of the thick MgO layer, we calculated a crystallite size of 11 nm for Pd from the rocking curve FWHM data. Again, no qualitative difference in EHE response between the differing Pd thicknesses was found.
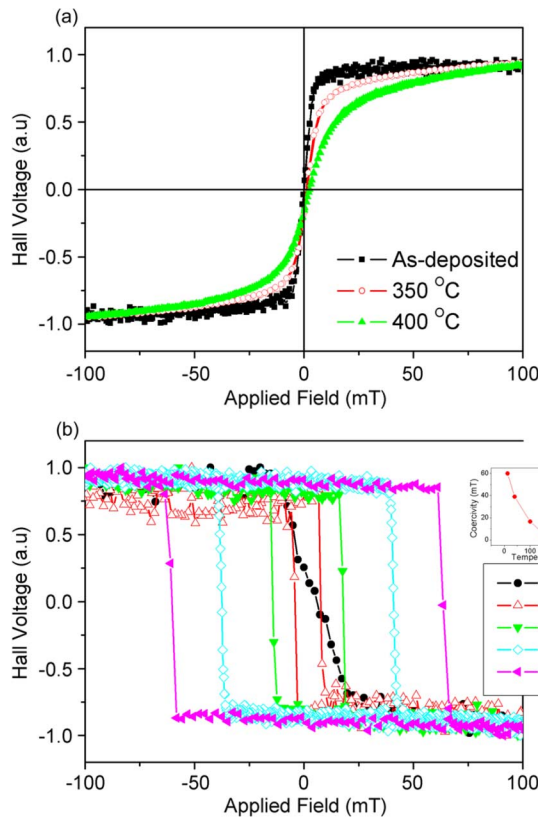
Fig. 3. (a) EHE response of MgO 1.4/CoFeB 0.6/Pd 5 after high temperature annealing. No stabilization of the PMA was observed. (b) Low-temperature EHE measurements of unannealed MgO 1.4/CoFeB 0.6/Pd 5. The film becomes ferromagnetic at approximately 228 K.

Since perpendicular anisotropy was enhanced due to optimum oxidation of the O_x/Co interface in the case of [10] and [11], we investigated the effect of high-temperature annealing on the MgO/CoFeB/Pd samples. We were still able to get a response from the EHE measurements with annealing temperatures up to 400 $^\circ$ C [Fig. 3(a)]. However, we did not see an enhancement of perpendicular anisotropy as a function of temperature in contradiction with the MgO/CoFeB/Pt case.

We investigated the superparamagnetic behavior by conducting low-temperature measurements on the MgO 1.4/CoFeB 0.6/Pd 5 sample. Below approximately 230 K, the sample is blocked and exhibits ferromagnetic behavior with H_c increasing exponentially as the temperature is decreased. This is shown in Fig. 3(b) and the inset. SQUID data (not shown) suggest the perpendicular axis is the easy axis at room temperature. The saturation magnetization of the CoFeB layer was determined from SQUID measurements to be 1.0 MA/m.

We have also reproduced (by sputtering) perpendicular anisotropy upon annealing the MgO/CoFeB/Pt as observed in [10]. The high-temperature response is different from that of MgO/CoFeB/Pd. This might be due to different migration characteristics of B with Pt or Pd capping.

As a final step, we investigated the effect of the application of an electric field on the unannealed MgO 1.4/CoFeB 0.6/Pd 5 system. A small but detectable change of coercivity was found; the change in H_c was 0.3% in an applied field of 250 MV/m. There was no detectable change in magnetization perpendicular to the plane according to the EHE measurement.

IV. CONCLUSION

Clear evidence is found for perpendicular magnetic anisotropy in the Pd/CoFeB/Pd bilayer system up to a CoFeB thickness of 0.6 nm. However, in the sputtered MgO/CoFeB/Pd system, where the CoFeB layer is amorphous, it may be superparamagnetic at room temperature despite the fact that it is a continuous film [15]. High-temperature annealing does not enhance the perpendicular anisotropy, which is not the case in the MgO/CoFeB/Pt system. By cooling below the blocking temperature (~ 230 K), it is possible to achieve coercivity, and a small effect of applied electric field on the coercivity of CoFeB was measured.

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