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We performed high field torque magnetometry measurements on CoO/[Co/Pt] magnetic multilayers that exhibit perpendicular exchange bias. We find that the antiferromagnet CoO layers strongly modify the uniaxial anisotropy of the multilayer structures. The strongest effects due to the CoO layers occur in the vicinity of the Néel temperature, where we observe a suppression of the first-order anisotropy and a smaller enhancement of the second-order anisotropy. This results in a nonmonotonic variation of the anisotropy with temperature and for selected samples a transition from perpendicular to in-plane and back to perpendicular anisotropy with increasing temperature.
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The exchange coupling of thin ferromagnetic (FM)/antiferromagnetic (AF) bilayer systems across their mutual interface can result in dramatic changes in the magnetic properties. The most common are exchange bias, i.e., a shift of the hysteresis loop as well as an increase in the coercivity when field cooled below the AF Néel temperature (T_N).[1] As a result, exchange biasing has become an important tool for controlling the magnetic orientation in magnetic devices and has been extensively studied in thin film[1,2] and nanostructured geometries.[3] However, the impact of the exchange coupling on the anisotropy of the FM in the vicinity of T_N and above the blocking temperature (T_B) is much less studied. The most extensive studies are for FM films coupled to AF single-crystal FeF_2 showing enhanced anisotropy even well above T_N of FeF_2.[4,5]

In this letter, we present high-field torque magnetometry measurements of perpendicularly exchange biased CoO/[Co/Pt] multilayers. We find that the CoO layers strongly modifies the perpendicular anisotropy of the [Co/Pt] multilayer film. The first order anisotropy (K_1) is strongly suppressed at T_N of the AF while the second order anisotropy (K_2) is enhanced. As a result, for selected films we observe the net anisotropy of the composite system goes from perpendicular to in-plane and then back to perpendicular with increasing temperature. These effects provide an approach to manipulate the magnetic anisotropy via temperature and may be useful in magnetic devices and recording media.

We studied the anisotropy of Co/Pt multilayer samples periodically interleaved with CoO. Sample 1, CoO(10 Å) $\times\{[\mathrm{Co}(4\ \text{Å})/\mathrm{Pt}(7\ \text{Å})]_4\mathrm{Co}(6\ \text{Å})\mathrm{CoO}(10\ \text{Å})\}_{10}$, and sample 2, CoO(10 Å)$\{[\mathrm{Co}(8\ \text{Å})/\mathrm{Pt}(7\ \text{Å})]_4\mathrm{Co}(6\ \text{Å})\mathrm{CoO}(10\ \text{Å})\}_{10}$, were deposited by magnetron sputtering where the CoO layer was formed by thermal oxidation of Co layers. Details of the deposition process can be found in Refs. 6 and 7. Both the [Co(4 Å)/Pt(7 Å)] and [Co(8 Å)/Pt(7 Å)] multilayer samples have perpendicular anisotropy although the amplitude is lower for the thicker Co layers. When field cools to low temperatures, both samples show exchange bias. The magnitude of the bias and coercive fields versus temperature are shown in Fig. 1. For sample 1, we determine $T_B \sim 175$ K and estimate $T_N \sim 250$ K from the onset of the exchange bias and the upturn in the coercive field respectively with decreasing temperature.[6] For sample 2, the blocking and Néel temperatures are reduced to $T_B \sim 100$ K and $T_N \sim 200$ K. The origin of this difference may result from slight strain driven microstructural changes that arise with increased Co layer thickness.

To quantify the anisotropy, we use the torque magnetometry option of a Quantum Design physical property measurement system. The samples were cooled in a 9 T field either perpendicular to the plane or in-plane and successive torque curves are measured with increasing temperature from 5 to 390 K. Representative torque curves are shown in Fig. 2 where the curves have been offset for clarity. Zero degrees corresponds to the applied field along the surface normal. In the high field regime, where the magnetization follows the applied field, the torque $\tau = -dE/d\theta$, where E is the angular

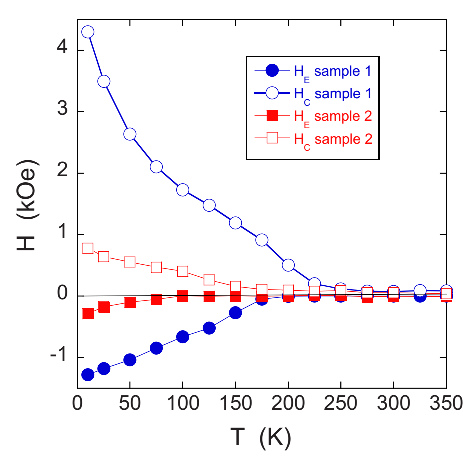

FIG. 1. (Color online) Magnetization results for perpendicular exchange-biased multilayers where sample 1 is CoO(10 Å) $\times\{[\mathrm{Co}(4\ \text{Å})/\mathrm{Pt}(7\ \text{Å})]_4\mathrm{Co}(6\ \text{Å})\mathrm{CoO}(10\ \text{Å})\}_{10}$ and sample 2 is CoO(10 Å)$\{[\mathrm{Co}(8\ \text{Å})/\mathrm{Pt}(7\ \text{Å})]_4\mathrm{Co}(6\ \text{Å})\mathrm{CoO}(10\ \text{Å})\}_{10}$. Plotted are the coercive field H_C and exchange bias H_E for each sample. From these results we estimate the Néel and blocking temperatures to be 250 and 200 K for sample 1 and 200 and 100 K for sample 2, respectively.

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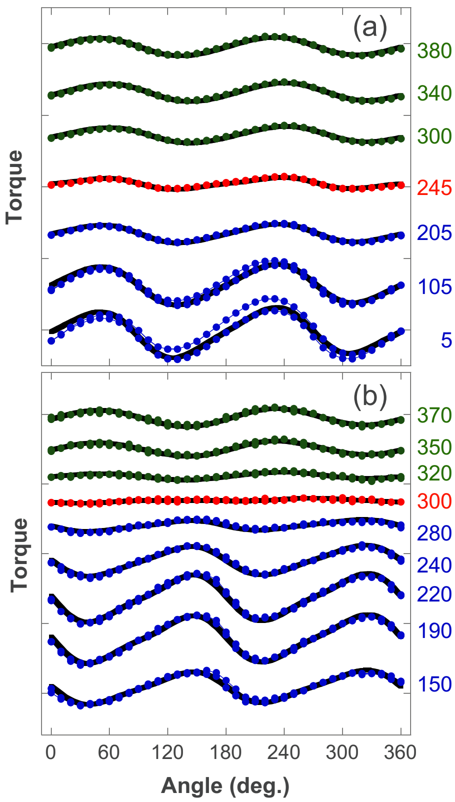

FIG. 2. (Color online) Representative torque curves for sample 1 (a) and sample 2 (b) measured at various temperatures (shown to the right of the graphs). The torque curves have been offset for clarity. For sample 1 there is a minimum in the torque amplitude near ~ 245 K. Below the blocking temperature the torque curves are hysteretic. For sample 2 the torque curves indicate a change in symmetry at 300 K, where the total anisotropy changes from in-plane to perpendicular with increasing temperature. The thick solid lines are fits to the torque curves using Eq. (1) and the results are shown in Fig. 3.

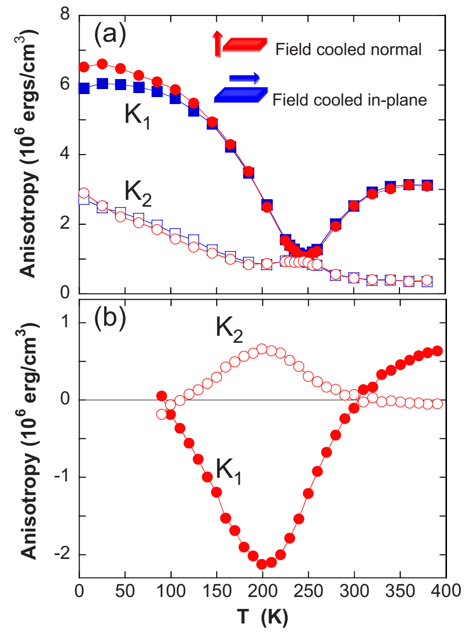

FIG. 3. (Color online) First order (K_1) and second order (K_2) anisotropies fitted from the torque data for sample 1 (a) and sample 2 (b). For sample 1 we include data for both in-plane (squares) and perpendicular (circles) field cooling. For sample 2 the torque curves below 80 K exhibit large hysteresis and become difficult to accurately fit.

dependence of the anisotropy energies. There are qualitative features that we would like to discuss prior to presenting the fitting results. (i) The torque curves are dominated by two-fold symmetry reflecting the uniaxial interfacial anisotropy of the Co/Pt multilayers and the thin film shape anisotropy. (ii) At low temperatures, the torque curves are hysteretic which persists up to T_B. Torque hysteresis in exchange biased systems is believed to result from irreversible processes in the AF grains.[8] (iii) The magnitude of the net anisotropy (magnetocrystalline+shape) is proportional to the amplitude of the torque curve. For the exchange-biased samples, the magnitude of the torque signal is nonmonotonic with temperature. For sample 1 [Fig. 2(a)] the torque signal amplitude initially decreases, reaches a minimum at $T\sim 245$ K and then increases with increasing temperature. For all temperatures the net anisotropy is perpendicular. For sample 2 [Fig. 2(b)] the torque signal has the opposite sign at $T=150$ K indicating a net in-plane anisotropy. The magnitude of the torque increases (becomes more negative), reaches a minimum at $T\approx 200$ K and then increases with increasing temperature and crosses over from in-plane to perpendicular at $T=300$ K.

To quantify the anisotropies the torque loops were fitted using the following energy expression:

$$E = K_1 \sin^2(\theta) + K_2 \sin^4(\theta) + K_{\mathrm{ud}} \cos(\theta - \varphi), \qquad (1)$$

where K_1 and K_2 are the first and second order uniaxial anisotropies and K_{ud} is a unidirectional anisotropy arising from the exchange-bias interaction (ϕ is the angle between the anisotropy and bias directions). K_1 includes both the magnetocrystalline anisotropy ($K_{1\ \mathrm{mc}}$) and the shape anisotropy ($-2\pi M_s^2$) such that $K_1 = K_{1\ \mathrm{mc}} - 2\pi M_s^2$. The fits are the thick solid lines in Fig. 2.

Figure 3 shows the results for K_1 and K_2 versus temperature. We do not show the results for K_{ud}, but these are consistent with the measured exchange bias in Fig. 1 and are small compared to the uniaxial anisotropies. While the cooling field direction has little effect on uniaxial anisotropies [Fig. 3(a)] there is a strong dependence on temperature. For sample 1, the anisotropy at low and high temperatures are consistent with the Co/Pt multilayer without the CoO. Surprisingly there is a large decrease in K_1 (and small increase in K_2) for intermediate temperatures resulting in a minimum in K_1 and a small maximum in K_2 at $T=245$ K and a subsequent increase in K_1 for higher temperature. This is in contrast to Co/Pt multilayers (with no CoO layers) where the anisotropy decreases monotonically with increasing temperatures.[9–11] These effects are also seen in the lower anisotropy sample 2 [Fig. 3(b)]. We see a strong decrease in K_1 and increase in K_2, which peak at 205 K. For $T > 205$ K, K_1 increases and changes sign at 300 K (going from in-plane to perpendicular anisotropy) and K_2 decreases to zero. Because of hysteresis in the torque curves, we were not able to extract reliable anisotropy values for $T < 80$ K. In both samples, the magnetic moment shows only a small monotonic decrease over the temperature range.

Since the anisotropy of the Co/Pt multilayer changes little over these temperature ranges, the strong suppression of the anisotropy must originate from the CoO. This is supported by the observation that K_1 reaches a minimum for each sample at the estimated T_N. The reduction of the total anisotropy (which is roughly the same magnitude for samples 1 and 2) suggests that the CoO in our samples is supplying an additional in-plane contribution to the anisotropy that opposes the Co/Pt multilayer perpendicular anisotropy. It is unlikely that lattice changes in the CoO layers below T_N (Ref. 12) (CoO transforms from cubic to monoclinic) and subsequent strain induced changes in the Co/Pt can explain our results. Neither the temperature dependence nor the magnitude of the anisotropies are consistent with this explanation. The temperature dependence are similar to the results of Leighton *et al.*[4] and Grimsditch *et al.*[5] who observed enhanced coercive fields in Fe/FeF_2 samples and induced anisotropy in Ni/FeF_2, respectively. In both cases, the induced anisotropy is in the direction of the AF layer anisotropy direction, the effects peaked at T_N and persisted for temperatures well above T_N. The high temperature enhancement is modeled as short-range order in the AF layer stabilized by the exchange interaction with the FM layer.[4,5] A similar model by Stamps and Usadel[13] finds that the induced anisotropy from the FM-AF interaction should scale with the AF magnetic susceptibility, which peaks at T_N.[4] In addition, the authors in Ref. 5 found that there is an induced first- and second-order anisotropy in the FM layer that were opposite in sign and the magnitude of induced K_2 at T_N is 1/3 K_1. These results are consistent with the magnitude and opposite trends in K_1 and K_2 observed in Fig. 3.

In the above models, the effective FM anisotropy includes an AF layer contribution.[4,5,13] This suggests that the net anisotropy of the CoO layers in our samples is in-plane. This is supported by measurements, which find stronger exchange bias when the cooling field is in-plane compared to out-of-plane.[6] This is also consistent with the symmetry of the torque hysteresis loss. One expects the maximum loss when the applied field is along the effective hard-axis of CoO. We find maximum torque hysteresis loss when the applied field is normal to the film [Fig. 2(a)], which is again consistent with a net in-plane anisotropy of the CoO layers. An in-plane anisotropy is expected for (111)-textured CoO films if you compare the in-plane and out-of-plane projections of the bulk CoO easy axis[6] but magnetostriction of the thin CoO layers may also contribute to the anisotropy direction.[14]

The present results can be compared to other reported findings. The nonmonotonic dependence of anisotropy on temperature may explain the nonmonotonic dependence of H_C for similarly grown $[Pd/Co]_3/CoO$ layers grown onto spherical nanoparticles.[15] For patterned structures, the coercive field more directly reflects the anisotropy than in continuous films where H_C is determined by domain wall pinning.[16] For Co/Pt multilayers interleaved with IrMn, it is observed that the temperature range of square hysteresis loop behavior extends to higher temperatures,[17] which suggests the anisotropy of the IrMn layers are perpendicular and support the Co/Pt anisotropy. Measurements of CoO/NiFe multilayers observed strong decrease of the perpendicular anisotropy with increasing temperature and attributed this to a temperature dependent surface anisotropy.[18] Finally experiments on spin-torque devices suggest that coupling of an AF on the sidewalls of devices can significantly alter the stability and reversal of the magnetic elements[19] at temperatures well above T_B. The present results suggest that the AF layers could contribute to the effective anisotropy of these devices.

More generally, our results show that it is possible to control the temperature dependence of perpendicular anisotropy by coupling to an AF layer with controlled anisotropy directions. This may be particularly important for applications such as magnetic recording, where control of the temperature dependence of the coercive field is desired. For traditional recording it is important to minimize the temperature dependence of H_C, where the AF layer could compensate for the loss of anisotropy in the FM with increased temperature. In contrast, for heat assisted magnetic recording it is important to maximize dH_C/dT at the writing temperature.[20] In addition we have shown that it is possible to switch the anisotropy from perpendicular to in-plane or in-plane to perpendicular with temperature, which may enable magnetic devices where anisotropies are tuned with temperature.

In conclusion, we have presented high field torque measurements of perpendicularly exchange biased CoO/[Co/Pt] multilayers. The results show that the CoO layer strongly affects the perpendicular anisotropy of the multilayer film with a maximum effect at T_N. The first order anisotropy is strongly suppressed while the second order anisotropy is enhanced. As a result, for selected films we observe the net anisotropy of the composite system go from perpendicular to in-plane and then back to perpendicular with increasing temperature.

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