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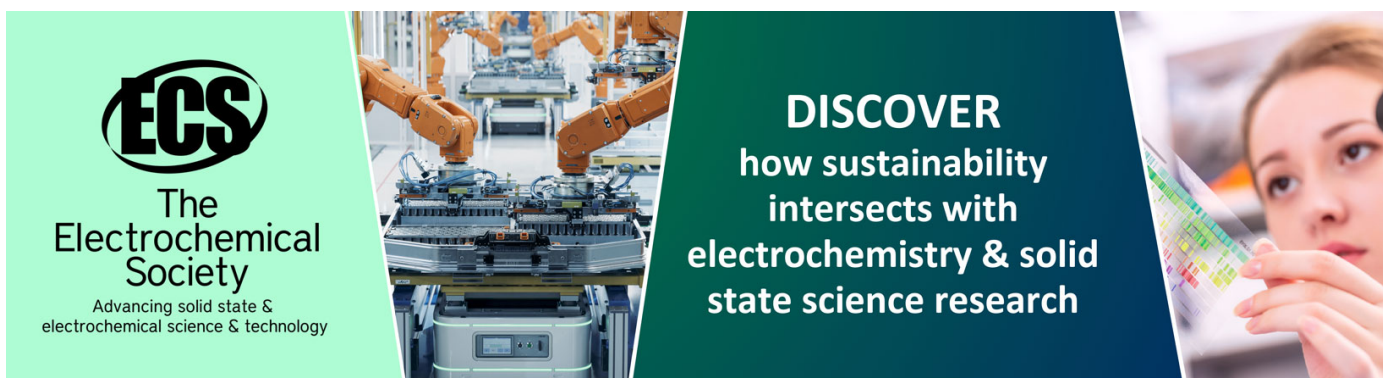
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Exchange-bias-like effect in $L1_0$ (111) FePt based pseudo spin valves

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Abstract. The coupling between hard FePt/CoFe and soft CoFe/NiFe layers through a Cu spacer has been studied in $L1_0$ (111) FePt(20)/CoFe(1.5)/Cu(3.5 or 4.5)/CoFe(2)/NiFe(3) (in nm) pseudo spin valves. The soft layer hysteresis loops exhibit clear shifts in the field axis (exchange bias-like) and a marked coercivity enhancement. The thickness of the Cu layer or the interface roughness influence the exchange bias properties of the systems. This interlayer coupling arises from the competition between dipolar and RKKY interactions between the layers.

1. Introduction

Exchange bias has been extensively investigated due to its intriguing basic properties [1] and its application in spintronic devices, such as magnetic read heads and magnetoresistive random access memories [2,3,4]. This phenomenon has been observed not only in antiferromagnetic/ferromagnetic (AFM/FM) systems [1], but also between the two FM layers in spin valves with AFM/FM/NM/FM (NM: non magnetic) structure [5], hard/soft exchange-coupled FM layers [6] and pseudo spin valves (hard-FM/NM/soft-FM layers) with in-plane anisotropy [7] or perpendicular anisotropy [8]. Recently, we have reported pseudo spin valves (hard-FM/NM/soft-FM layers) with tilted anisotropy [9,10] for use in tilted polarizer spin torque oscillators [11,12]. Therefore it is interesting to study the exchange coupling between the free and fixed layers in our pseudo spin valves with tilted anisotropy.

In this paper, exchange bias-like properties in $L1_0$ (111) FePt/CoFe/Cu(3.5 or 4.5 nm)/CoFe/NiFe/Ta pseudo spin valves are evidenced by both a shift of the CoFe/NiFe soft layer loop and a marked increase in the free layer coercivity during the switching of the hard FePt/CoFe fixed layer.

2. Experiments

Films with the structure of underlayer/ $L1_0$ (111) Fe₅₃Pt₄₇(20)/ Co₅₀Fe₅₀(1.5)/ Cu(3.5 or 4.5)/Co₅₀Fe₅₀(2)/Ni₈₀Fe₂₀(3) (in nm) have been deposited on thermally oxidized Si substrates using a magnetron sputtering system. $L1_0$ Fe₅₃Pt₄₇ (FePt) alloy films have been fabricated at

a nominal substrate temperature of 700° C and subsequently *in-situ* annealed at the same temperature for 10 min. Apart from films sputtered directly on SiO₂, two different types of underlayers, Ta(6 nm) and Ta(6 nm)/Pt(3 nm) have been used to promote the (111)-preferred texture of the L₁₀ FePt layer [9]. Permalloy (Ni₈₀Fe₂₀, NiFe) free layers, thin Co₅₀Fe₅₀ (CoFe) spin enhancing layers, and 5-nm-thick Ta capping layers have been deposited at room temperature. Magnetic properties are characterized using a Physical Parameter Measurement System (PPMS) equipped with a Vibrating Sample Magnetometer (VSM) option with a maximum field of 90 kOe. The high-field hysteresis loops are carried out up to ±90 kOe. The loops of the soft layers are performed using 1 kOe maximum field. Surface roughness is studied using atomic force microscopy (AFM). All the FePt layers, regardless of the type of underlayer, show (111)-preferred orientation and their magnetic properties exhibit tilted anisotropy [9].

3. Results and discussion

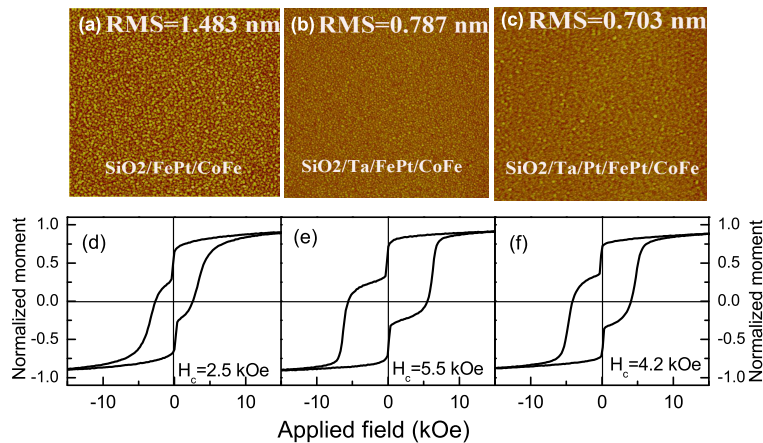


Figure 1. AFM images of fixed layers, and in-plane high-field VSM hysteresis loops of full spin valves grown on these fixed layers, with (a,d) SiO₂/FePt/CoFe; (b,e) SiO₂/Ta/FePt/CoFe; (c, f) SiO₂/Ta/Pt/FePt/CoFe. The rms roughness is marked in the AFM images.

Figure 1 (a)-(c) shows AFM images with 5 $\mu\text{m} \times 5 \mu\text{m}$ scanning area of FePt/CoFe fixed layers grown on different underlayers. Figure 1 (d)-(f) shows the corresponding high-field hysteresis loops of the full spin valve stacks grown on the same underlayers and under the same conditions. All samples were measured to ±90 kOe but here the loops are zoomed in to ±15 kOe for clarity. FePt/CoFe deposited directly on SiO₂ has the roughest surface with around 1.483 nm rms roughness. This type of fixed layer also exhibits the lowest coercivity. However, FePt/CoFe on a Ta/Pt hybrid underlayer has the smoothest surface with 0.703 nm rms roughness, as shown in Fig. 1 (c), and the coercivity and squareness of the fixed layer is much higher. Removing the Pt, as in the fixed layer grown on Ta underlayer, results in a slightly higher rms roughness of 0.787 nm and a slightly lower fixed layer coercivity.

Figure 2 displays the low-field hysteresis loops of the different pseudo spin valves after saturation in +90 kOe. The sample with 4.5 nm Cu which is directly sputtered on SiO₂ exhibits no loop shift (Fig. 2(a)). However, when the FePt layer is deposited on a Ta or a Ta/Pt buffer layer (Fig. 2 (c) and (d)), the loops exhibit shifts towards positive fields. Remarkably, the loop shift of the sample deposited on Ta/Pt ($H_E = +42$ Oe) is significantly larger than the one deposited on Ta ($H_E = +22$ Oe). The shift to positive fields implies that the layers are antiferromagnetically coupled. This type of coupling indicates that RKKY interactions are dominant for these samples. As seen in Fig. 1, the main differences between the samples grown on the two different underlayers are the coercivity of the hard layer and the root-mean-square

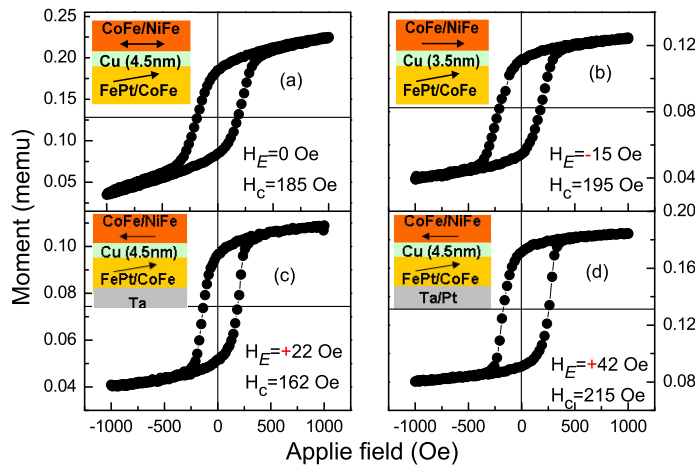


Figure 2. In-plane low-field VSM hysteresis loops of the soft layers in (a) $\text{SiO}_2/\text{FePt}/\text{CoFe}/\text{Cu}(4.5 \text{ nm})/\text{CoFe}/\text{NiFe}/\text{Ta}$; (b) $\text{SiO}_2/\text{FePt}/\text{CoFe}/\text{Cu}(3.5 \text{ nm})/\text{CoFe}/\text{NiFe}/\text{Ta}$; (c) $\text{SiO}_2/\text{Ta}/\text{FePt}/\text{CoFe}/\text{Cu}(4.5 \text{ nm})/\text{CoFe}/\text{NiFe}/\text{Ta}$ and (d) $\text{SiO}_2/\text{Ta}/\text{Pt}/\text{FePt}/\text{CoFe}/\text{Cu}(4.5 \text{ nm})/\text{CoFe}/\text{NiFe}/\text{Ta}$. Each magnetization configuration is inserted to the related figure to explain the coupling type between the free and fixed layers.

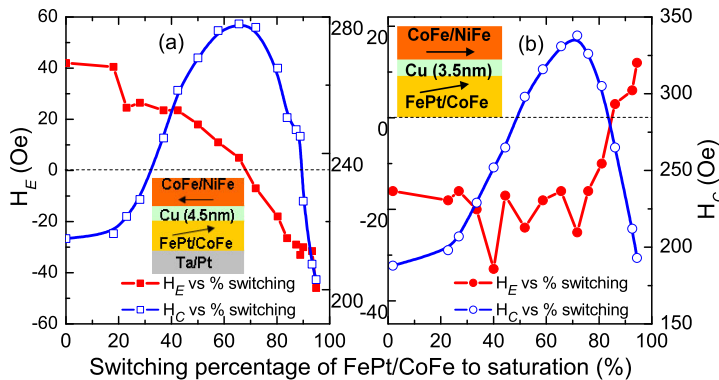


Figure 3. Coercivities and exchange bias fields of the soft layers vs. percentage of hard magnetic FePt/CoFe switching for (a) $\text{SiO}_2/\text{Ta}/\text{Pt}/\text{FePt}/\text{CoFe}/\text{Cu}(4.5 \text{ nm})/\text{CoFe}/\text{NiFe}/\text{Ta}$ and (b) $\text{SiO}_2/\text{FePt}/\text{CoFe}/\text{Cu}(3.5 \text{ nm})/\text{CoFe}/\text{NiFe}/\text{Ta}$. The dashed lines correspond to 0 Oe shift and the insets are schematic for exchange coupling between the free and fixed layers.

(rms) roughness. Given that the RKKY interactions for these three samples should be roughly the same; either the roughness or the hard layer coercivity should control the bias. At first approximation the hard layer H_C should play only a minor role in the bias assuming H_C is much larger than the field applied for the soft-layer loops, since between $\pm 1 \text{ kOe}$ the hard layer should remain unaltered and almost fully saturated. On the other hand the Néel (orange peel) dipolar coupling depends strongly on the roughness [13], where smaller roughness implies reduced coupling. When reducing the dipolar coupling for the smoother sample, the RKKY contribution becomes proportionally stronger, leading to an increase in positive loop shift.

Interestingly, when the Cu thickness for the sample without buffer layer is decreased to 3.5 nm, an obvious shift to negative fields, $H_E = -15 \text{ Oe}$, is obtained (Fig. 2(b)). Negative shifts imply a ferromagnetic coupling between the soft and hard layer. The change from antiferromagnetic coupling to ferromagnetic coupling and the increase of H_E for thinner Cu layers can be tentatively ascribed to the enhanced dipolar interactions due to thinner Cu interlayers [13]. However, RKKY coupling between the layers should also play a role since due to its oscillatory character 3.5 nm of Cu could be in the region of ferromagnetic coupling while 4.5 nm could be in the antiferromagnetic coupling region [14].

Figure 3 shows the coercivities and exchange bias fields of the soft layers vs. switching percentage of FePt/CoFe bilayers in spin valves for two different samples: (a) no-underlayer and 3.5 nm Cu; and (b) Ta/Pt buffer layer and 4.5 nm Cu. Here the samples are first saturated under + 90 kOe, then a negative field is applied and subsequently followed by a low-field (1 kOe) loop. The procedure is repeated for increasing negative fields. For small negative fields the hard layer remains unchanged, so no effect is observed in the soft layer loop. Eventually the hard layer starts to reverse, where the switching percentage of FePt/CoFe is defined as the ratio of the magnetization of FePt/CoFe at each negative inverse field to its saturation magnetization. When the hard layer reversal starts, the hysteresis loop of the soft layer also changes. The soft-layer loop shift decreases, finally changing sign, while the coercivity exhibits a maximum (which takes place at approximately 70% switching of the FePt/CoFe layer). Interestingly, the increase of coercivity, ΔH_C is different in the two cases. This implies that since ΔH_C is also a sign of the interlayer coupling, it depends on the different parameters such as roughness or Cu thickness.

4. Conclusion

In summary, exchange bias-like effects are experimentally observed in $L1_0$ (111)-oriented FePt based all-metallic-ferromagnetic Hard-FM/Cu/Soft-FM spin valves. The loop shift and the coercivity of the CoFe/NiFe soft layer correlate with interface roughness, the Cu thickness and the switching of the hard layer. The interlayer coupling is an interplay between RKKY and dipolar coupling between the hard and soft layer.

Acknowledgments

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