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Pinned synthetic ferrimagnets with perpendicular anisotropy and tuneable exchange bias

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Pinned synthetic ferrimagnets (syFerri) with perpendicular-to-plane magnetic anisotropy, of the form $AP_1/Ru/AP_2/FeMn$ [where AP_1 and AP_2 are (Co/Pt) multilayers], have been prepared and characterized. The magnitudes of the exchange bias fields of both AP_1 and AP_2 can be tuned at room temperature by simply varying the relative number of (Co/Pt) repeats in each multilayer. This effect can be quantitatively interpreted by considering the different energy contributions involved during magnetization reversal. Moreover, from the values of these fields, the characteristic parameters of the system (i.e., coupling strength through the Ru and $AP_2/FeMn$ pinning energy), can be evaluated. Interestingly, an extended plateau with a virtually constant magnetization is observed around zero field when the number of Co/Pt repeats in AP_1 is equal or larger than in AP_2. This is very appealing for field sensor or memories applications using spin valves or tunnel junctions with perpendicular anisotropy, since it offers a large dynamic range over which the magnetic configuration of the syFerri remains stable.
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Recently, in spin-valve based read heads for high density magnetic recording media,[1] the replacement of the traditional antiferromagnetic (AFM) exchange layer by synthetic antiferromagnets (syAFM) has been found to be very appealing, since syAFM considerably enhance the thermal and magnetic stability of these sensors and reduce the magnetostatic field created by the pinned layer on the free layer in submicronic devices.[2] Typically, a syAFM consists of two ferromagnetic (FM) layers separated by a nonmagnetic spacer, such as Ru (6–10 Å thick), which couples them antiferromagnetically due to the Ruderman–Kittel–(Kasuya)–Yosida [RK(K)Y] interaction.[3]

All syAFM-based spin valves elaborated so far exhibit an in-plane magnetic anisotropy. Just recently, spin valves and tunnel junctions with perpendicular-to-plane anisotropy have also been developed.[4] However, they do not make use of syAFM. Studies on syAFM-like systems with perpendicular anisotropy are very scarce[5] and the effect of varying the relative thickness of the two FM layers in contact with Ru has only been systematically investigated in in-plane syAFM.[6] Nevertheless, a few studies on the physics of antiferromagnetically coupled multilayers with perpendicular anisotropy have been reported.[7,8]

In this letter, we demonstrate the feasability to grow pinned synthetic ferrimagnets (syFerri) with perpendicular anisotropy, exhibiting tuneable exchange bias at room temperature. The systems consist of two antiferromagnetically coupled (Pt/Co) multilayers (ML), denoted as AP_1 and AP_2, in which AP_2 is, in turn, exchange biased with an AFM.[9] The switching fields of both AP_1 and AP_2 can be easily tuned by simply varying the relative number of (Pt/Co) repeats in each multilayer.

A series of pinned synthetic ferrimagnets with the composition Pt (50 Å)/[Co (5 Å)/Pt(20 Å)]$_n$/Co(5 Å)/Ru(7 Å)/[Co(5 Å)/Pt(20 Å)]$_3$/Co(5 Å)/FeMn(130 Å)/Pt(20 Å), i.e., $AP_1/Ru/AP_2/FeMn$, with $n=1$, 2, 3, 4, and 5, were deposited onto thermally oxidized Si substrates by dc magnetron sputtering. The AP_1 multilayer contains a variable number of Co layers, i.e., $n_{AP1}=n+1$, whereas AP_2 contains always 4 Co layers. All depositions were performed at room temperature. A stray field perpendicular to plane is known to exist over the substrate area in the sputtering unit. Hysteresis loops of as-deposited samples were recorded using extraordinary Hall effect, with magnetic field applied perpendicular to the film direction.[10]

Figure 1 shows the hysteresis loops of the pinned syFerri with $n_{AP1}=2$, 3, 4, and 6. The magnetic configurations of AP_1 and AP_2 multilayers are indicated by the thin and thick arrows, respectively. It can be seen that when the field is reduced from positive to negative saturation, the magnetization of AP_1 (M_{AP1}) always switches before that of AP_2, M_{AP2}, at a positive field denoted by $H^+_{E,AP1}$. A broad plateau is then observed around zero field, over which the two multilayers are in antiparallel magnetic configuration. When the field is further reduced, the magnetization of the AP_2 layer (M_{AP2}) finally switches at a negative field $H^+_{E,AP2}$. Interestingly, for $n_{AP1}=2$, the switching of M_{AP2} is accompanied by a backswitching (i.e., spin-flip) of M_{AP1}, due to the antiferromagnetic RK(K)Y interaction through Ru. Finally, M_{AP1} switches down again at a slightly larger negative field.

When increasing the field from negative to positive saturation, significant differences in the magnetization reversal process are observed depending on the value of n_{AP1}.

(1) For $n_{AP1}=2$ and 3, M_{AP1} switches first at a characteristic negative field $H^-_{E,AP1}$. Note that since the energy balance which determines this switching field is exactly the same as the one which determines the switching field of M_{AP1} at decreasing field from positive saturation, the rela-

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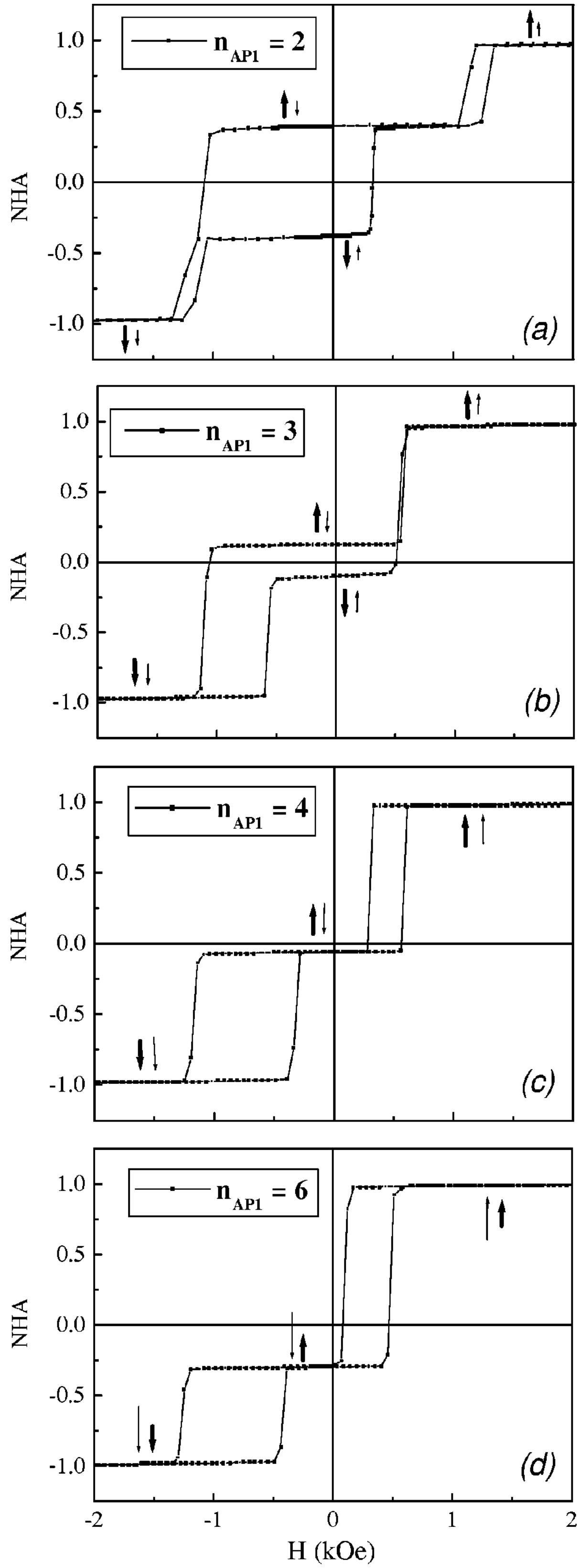

FIG. 1. Normalized Hall amplitude hysteresis loops of syFerri of the form AP_1/Ru/AP_2/FeMn, with $n_{AP1}=2$, 3, 4, and 6 (where n_{AP1} is the number of Co layers in the AP_1 multilayer). The thin and thick arrows indicate the magnetization state of multilayers AP_1 and AP_2 in the syFerri, respectively.

tionship $H^-_{E,AP1}=-H^+_{E,AP1}$ is observed. As the field is further increased, M_{AP2} switches. In the case $n_{AP1}=2$, this switching is again accompanied by a backswitching of M_{AP1}. In this case, another transition occurs at a larger positive field corresponding to the reversal of M_{AP1}. Note that the backswitching of M_{AP1} is not observed for $n_{AP1}=3$ because it would cost too much Zeeman energy.

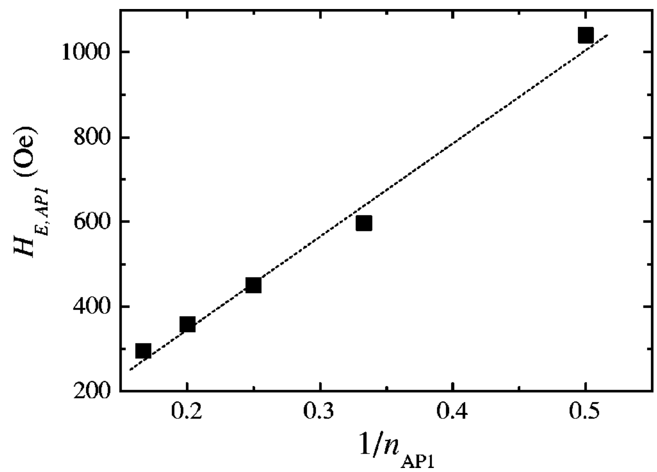

FIG. 2. Dependence of the exchange bias field of AP_1 $1/n_{AP1}$, where n_{AP1} designates the number of Co layers in AP_1.

(2) For $n_{AP1}\geqslant 4$, M_{AP2} switches first. This results in an extended plateau with constant magnetization around zero field. We point out that in these cases, there is only one stable remanent state of the system in zero field. This is a situation of practical interest for device applications in order to use such a synthetic pinned layer as a reference layer in spin valves or tunnel junctions with perpendicular magnetization. At a larger positive field, the magnetization M_{AP1} reverses towards positive saturation.

The differences in the magnetization curves of the different systems can be understood as the result, in each syFerri, of an interplay between the Zeeman energy, the exchange energy across the Ru spacer and the pinning energy with the FeMn. The purpose of the following calculations is to relate the values of the AP_1 and AP_2 switching fields with the coupling energy per unit area through the Ru spacer (A_{Ru}) and the coupling energy per unit area with the antiferromagnetic layer ($A_{pinning}$). These calculations assume that the system is always able to reach its lowest energy minimum, i.e., as a first step, we do not try to describe the irreversibility associated with the switching of M_{AP1} and M_{AP2}.

Let us first consider the switching of AP_1 when decreasing field from positive saturation. This switching occurs at a positive field when the gain in coupling energy due to the antiferromagnetic coupling through the Ru spacer balances the cost in Zeeman energy due to the negative orientation of M_{AP1} in the positive field. If t_{Co} is the thickness of the individual Co layers and Ms_{Co} its saturation magnetization, then the bias field of AP_1, $H_{E,AP1}$ (evaluated as the average of the two switching fields in the AP_1 minor loop), is given by:

$$n_{AP1}Ms_{Co}t_{Co}H_{E,AP1}=A_{Ru}. \tag{1}$$

This expression predicts a linear variation of $H_{E,AP1}$ vs $1/n_{AP1}$, provided that A_{Ru} is constant. If one plots $H_{E,AP1}$ as a function of $1/n_{AP1}$, a linear dependence of $H_{E,AP1}$ is experimentally observed, as shown in Fig. 2. Assuming $Ms_{Co}=1450$ emu/cm^3 (bulk value), the slope of $H_{E,AP1}$ ($1/n_{AP1}$) in Fig. 2 allows us to determine A_{Ru}. One obtains $A_{Ru}=0.134$ erg/cm^2. Note that the possibility to tune perpendicular exchange bias by changing the number of Co/Pt repeats has already been reported in the literature.[11–13] The coercivity of AP_1 can be also easily determined from the AP_1 minor loops. The coercive field increases with n_{AP1}, as commonly observed in (Pt/Co) multilayers, from 95 Oe for $n_{AP1}=2$ to 200 Oe for $n_{AP1}=6$. This is due to an increase of the overall perpendicular anisotropy in AP_1 with the number of Pt/Co interfaces, as well as to the increase of structural defects, which may act as pinning centers for domain wall propagation.

The switching of M_{AP2} at negative fields occurs when the Zeeman energy brought by the applied field exceeds the cost in energy to overcome both the antiferromagnetic coupling through the Ru spacer and the exchange bias energy with FeMn. The associated coercivity can be clearly seen for $n_{AP1}=4$ and 6 from the width of the AP_2 minor loops [Figs. 1(c) and 1(d)]. Note that the coercivity of AP_2 is larger than for AP_1 for the same number of repeats due to the exchange biasing of AP_2 with FeMn.[9] The bias field of AP_2, $H_{E,AP2}$, can be evaluated by considering the shift of the AP_2 minor loops for $n_{AP1}=4$ and 6. One finds $H_{E,AP2}$ to be around 810 Oe. $H_{E,AP2}$ is then related to the coupling constants by the expression

$$n_{AP2}\mathrm{Ms}_{Co}t_{Co}H_{E,AP2}=-(\mathrm{A}_{Ru}+\mathrm{A}_{pinning}). \tag{2}$$

This relationship allows to calculate $A_{pinning}$ from the knowledge of $H_{E,AP2}$. Namely $A_{pinning}=0.068\ \mathrm{erg/cm^2}$.

The values of $H_{E,AP2}$ in the syFerri are significantly larger than the ones for Pt/Co ML exchange biased with FeMn (i.e., about 810 Oe, compared 150 Oe in simple ML + FeMn structures).

It is also worthwhile to illustrate why the layers switch the way they do and not in the reverse order. Note that, when decreasing field from positive saturation, if M_{AP2} switched before M_{AP1}, Eqs. (1) and (2) would no longer govern the reversal. Instead, the hypothetical bias field of AP_2, $H_{E,AP2}$(hypo) would be given by the following equation:

$$n_{AP2}\mathrm{Ms}_{Co}t_{Co}H_{E,AP2(hypo)}=(A_{Ru}-A_{pinning}). \tag{3}$$

Comparing the values of $H_{E,AP1}$ and $H_{E,AP2}$(hypo) [Eqs. (1) and (3)], it is found that M_{AP2} would reverse before M_{AP1} only if

$$\frac{A_{Ru}-A_{pinning}}{n_{AP2}}>\frac{A_{Ru}}{n_{AP1}}. \tag{4}$$

Taking the previously determined values of A_{Ru} and $A_{pinning}$ one finds that Eq. (4) is never fulfilled, which explains why M_{AP1} always switches first when the field is decreased from positive saturation.

Analogously, when the field is increased from negative saturation, it can be shown that M_{AP2} reverses before M_{AP1} only if

$$\frac{A_{Ru}+A_{pinning}}{n_{AP2}}>\frac{A_{Ru}}{n_{AP1}}. \tag{5}$$

Condition (5) is fulfilled for $n_{AP1}=3$, 4, 5, and 6 and, consistently, it is experimentally observed that M_{AP2} reverses before M_{AP1} for $n_{AP1}=4$, 5, and 6. Similarly, Eq. (5) is not fulfilled for $n_{AP1}=2$ in agreement with the experimental observation that M_{AP1} switches first. For $n_{AP1}=3$, although inequality (5) is fulfilled, M_{AP1} switches before M_{AP2} [see Fig. 1(c)]. This is because the coercive field in AP_2 is always larger than in AP_1.

In conclusion, it has been shown that pinned synthetic ferrimagnets with perpendicular anisotropy, can be prepared. The bias fields of both ML constituting the syFerri can be tuned at room temperature by varying the relative number of Co/Pt repeats comprised in each ML and their values are determined by the exchange constants A_{Ru} and $A_{pinning}$. However, an extended plateau with constant magnetization around zero field and a single stable remanent state is obtained when the condition $n_{AP1}>A_{Ru}/(A_{Ru}+A_{pinning})\,n_{AP2}$ is fulfilled. These properties are particularly useful to implement spin valves or tunnel junctions with perpendicular anisotropy and enhanced magnetic stability.

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