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Anisotropic magnetic switching along hard [1 1 0]-type axes in Er-doped $DyFe_2/YFe_2$ thin films

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ABSTRACT

Epitaxial-grown $DyFe_2/YFe_2$ multilayer thin films form an ideal model system for the study of magnetic exchange springs. Here the $DyFe_2$ (YFe_2) layers are magnetically hard (soft). In the presence of a magnetic field, exchange springs form in the YFe_2 layers. Recently, it has been demonstrated that placing small amounts of Er into the centre of the YFe_2 springs generates substantial changes in magnetic behavior. In particular, (*i*) the number of exchange-spring states is increased dramatically, (*ii*) the resulting domain-wall states cannot simply be described as either Néel or Bloch walls, (*iii*) the Er and Dy magnetic loops are strikingly different, and (*iv*) it is possible to engineer Er-induced magnetic exchange-spring collapse. Here, results are presented for Er-doped (1 1 0)-oriented $DyFe_2$ $(60\,Å/YFe_2(240\,Å)_{15}$ multilayer films, at 100 K in fields of up to 12 T. In particular, we contrast magnetic loops for fields applied along seemingly equivalent hard-magnetic [1 1 0]-type axes. MBE-grown cubic Laves thin films offer the unique feature of allowing to apply the magnetic field along (*i*) a hard out-of-plane [1 1 0]-axis (the growth axis) and (*ii*) a similar hard in-plane $[\bar{1}10]$-axis. Differences are found and attributed to the competition between the crystal-field interaction at the Er site and the long-range dipole-dipole interaction. In particular, the out-of-plane [1 1 0] Er results show the existence of a new magnetic exchange spring state, which would be very difficult to identify without the aid of element-specific technique of X-ray magnetic circular dichroism (XMCD).

1. Introduction

Switching mechanisms in thin film bits will always be of interest to the magnetic recording industry. In particular, it has been suggested that bilayer films consisting of hard and soft layers should find a role in beating the so-called superparamagnetic limit, where $KdV \rightarrow kT$, Weller and Moser [1]. Here K and dV are the anisotropy and change in volume, respectively, of the magnetic bit. Thus if we wish to decrease dV, it is imperative to move to higher anisotropy K materials. However the latter inevitably leads to an undesired need for higher write fields. This problem has been addressed by Suess et al., [2] and Krone et al., [3], who suggest combining the hard bit with a soft magnetic layer. In such bilayer systems, magnetic exchange springs set in the soft layer act as magnetic levers, thereby reducing the field required to switch the magnetic bit.

More recently, magnetic switching mechanisms have been studied in molecular beam grown (MBE)-multilayer films of the cubic Laves $DyFe_2/YFe_2$ at 100 K [4–6]. Such films are characterized by very sharp Dy/Y interfaces, and form a very good test bed for the study and manipulation of magnetic exchange-spring systems. Here, the $DyFe_2$ layers are hard while the YFe_2 layers are magnetically soft. Thus in the presence of an applied field, magnetic exchange springs are set up in the YFe_2 layers. Specifically, switching scenarios have been described for a $DyFe_2(60\,Å)/YFe_2(240\,Å)_{15}$ multilayer, for fields applied in-plane along either an easy [001]-axis or hard in-plane $[\bar{1}10]$ axis. More recently, a particular study of an Er-doped $DyFe_2/YFe_2$ multilayer has been performed, which shows that (*i*) the Er moments can be switched before those of the harder Dy layers, and (*ii*) up to 10 different exchange springs states are accessed during magnetic

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reversal [6]. However, all of this work has been performed with magnetic fields applied along *in-plane* easy [001] or hard $[\bar{1}10]$ axes.

Here we present results for an Er-doped (110)-oriented multilayer $\mathrm{DyFe_2(60\,Å)/YFe_2(120\,Å)/ErFe_2(4\,Å)/YFe_2(120\,Å)_{15}}$ film, again at 100 K for comparative purposes, in fields of up to ±12 T applied along an *out-of-plane* [110]-axis. Thus we are able to contrast magnetization curves for fields applied along seemingly equivalent [110] and $[\bar{1}10]$-axes. Both axes are illustrated in Fig. 1. Thin films of the cubic Laves structure offer the unique feature of allowing the magnetic field to be applied along (*i*) a hard out-of-plane [110]-axis (the growth axis) and (*ii*) a similar hard in-plane $[\bar{1}10]$-axis. In practice, differences are found in both the Dy and Er magnetic loops. In particular, the latter are attributed to competition between the predominantly cubic crystal-field interaction at the Er site, and the long range dipole-dipole interaction which confers in-plane anisotropy. In short, the out-of-plane [110] Er results reveal the existence of a new magnetic exchange-spring state $\mathrm{Dy_B}[010]/\mathrm{Er_S}[\bar{1}1\bar{1}]$, while its $[\bar{1}10]$ counterpart $\mathrm{Dy_B}[010]/\mathrm{Er_S}[11\bar{1}]$ appears to be either unstable or weakly stable and as such is bypassed by exchange spring collapse [6]. Here, the subscript B (S) in, say, the spring state $\mathrm{Dy_B}[010]/\mathrm{Er_S}[\bar{1}1\bar{1}]$ refers to Dy in the *bulk* $\mathrm{DyFe_2}$ layer, Er in the *spring*, respectively (see Ref. [6] for more details and discussion).

Finally, we note that while this and most of the previous work has been concerned with essentially DC magnetic switching, this work will also have relevance for picosecond switching in $\mathrm{DyFe_2/YFe_2}$ multilayer systems, as described by Shelford et al., [7].

2. Experimental details and results

Details of (*i*) the growth of the MBE-grown 4000 Å thick films used in this work, and (*ii*) determination of both the Dy and Er magnetization loops, can be found in Wang et al., [8] and Stenning et al., [6], respectively, and will not be reiterated here. Once again, X-ray magnetic circular dichroism (XMCD) experiments were performed using the Er $M_{4,5}$ (1405, 1446 eV) and Dy $M_{4,5}$ (1293, 1327 eV) absorption edges, in fluorescence detection. A review of this technique can be found in Ref. [9]. We estimate that at 1300 eV, the penetration depth is ~ 300 nm. Finally, a schematic representation of the experiments, illustrating the two orientations used, can be seen in Fig. (2).

The resulting Er and Dy loops, for fields applied along the [110] growth-axis, can be seen in Fig. 3(a,b).

An examination of these magnetization curves reveals several features. In particular, the Er loop is inverted with respect to that of the Dy. Here the Dy loop follows the *norm* in that the Dy moment is positive in a positive magnetic field. By contrast, the Er moment is negative. Here the sign of the Er moment is dictated by the behavior of the exchange spring. In a large magnetic field the Fe spins in the center of the $\mathrm{YFe_2}$ springs are roughly parallel to those of the Dy moments. However the Er is AF-coupled to its Fe counterparts. Thus the Er-loop is inverted with respect to that of the Dy. Note also that the coercive field of the Er is much less than that of the Dy. The coercivity of the Er loop is determined primarily by the bending field of the exchange spring, typically ~0.5 T in $\mathrm{DyFe_2(60\,Å)/YFe_2(240\,Å)_{15}}$ multilayer systems [4–6].

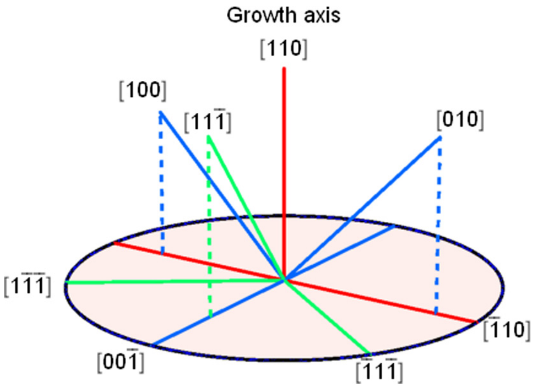

Fig. 1. The principal axes in an MBE-grown thin film of the cubic Laves phase $R\mathrm{Fe_2}$ intermetallic compound. The [110]-direction (the growth axis) is perpendicular to the plane of the film. The easy (hard) axes ⟨100⟩ (⟨110⟩) for the Dy ions are shown in blue (red), respectively. The easy ⟨111⟩ axes for the Er ions are shown in green.

For comparative purposes, similar loops for fields applied long the in-plane $[\bar{1}10]$-axis can be seen in Fig. 4(a,b).

On comparing the two magnetization curves for these two seemingly equivalent hard-axes it is apparent that the out-of-plane Er loop of Fig. 3(a) shows a definite inflection at around ±0.5 T, which is not apparent in the in-plane loop of Fig. 4(a). In fact, the latter is an excellent example of 'exchange-spring collapse', as described in Ref. [6].

In this paper we provide an explanation for the differences in Er-switching behavior, for the two seemingly equivalent directions of magnetization. In particular, it will be argued that the inflection point in Fig. 3(a) reveals the existence of a stable exchange state $\mathrm{Dy_B}[010]/\mathrm{Er_S}[\bar{1}11]$, which we shall refer to as a *stepping stone state* (C2), roughly half way between the maximum and minimum Er Signals. However, its' in-plane counterpart $\mathrm{Dy_B}[010]/\mathrm{Er_S}[11\bar{1}]$ (B2) is unstable and is bypassed by exchange spring collapse. Schematic diagrams of the two switching mechanisms in question can be seen in Figs. 5 (a,b) for fields applied along the [110] and $[\bar{1}10]$-axes, respectively. Note that in both cases the Dy moments remain fixed along the [010]-axis, while the Er moments are reversed.

However, before providing an explanation of the switching scenarios sketched out in Fig. 5 (a,b) it is advantageous to examine all possible sources of anisotropy and asymmetry.

3. Cubic crystal-field anisotropy terms

In free standing $R\mathrm{Fe_2}$ Laves phase compounds, the principle source of anisotropy arises from the interaction of the 4th and 6th order multipolar charge distributions of the R^{3+} $4f^n$ electrons with high-order electric field gradients. This electrostatic interac-

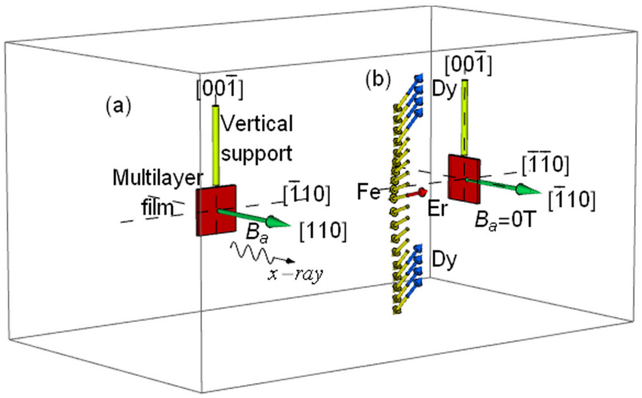

Fig. 2. Schematic diagrams illustrating the two orientations used in the XMCD experiment, with the X-ray beam and field B_a applied along **(a)** the out-of-plane ([110], and **(b)** the in-plane ($[\bar{1}10]$)-axis, respectively. Also shown in (b) is a schematic diagram illustrating the AF coupling between the Dy (blue) and Er (red) moments with those of the Fe (yellow). Note that even in zero field, there is an exchange spring present in the Fe-sublattice. For the experiments depicted in (b) the film was orientated at a small glancing angle of 7°, with respect to the X-ray beam. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)