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Journal of Magnetism and Magnetic Materials 257 (2003) 270–273

www.elsevier.com/locate/jmmm

Anisotropic magneto-resistance in an epitaxial (1 1 0) $DyFe_2$ film: a meta-stable magnetic state at 100 K

J.-M.L. Beaujour[a], G.J. Bowden[a,*], A.A. Zhukov[a], B.D. Rainford[a], P.A.J. de Groot[a], R.C.C. Ward[b], M.R. Wells[b], A.G.M. Jansen[c]

[a] *Department of Physics and Astronomy, University of Southampton, SO17 1BJ Southampton, UK*
[b] *Clarendon Laboratory, Oxford University, Oxford OX1 3PU, UK*
[c] *Grenoble High Magnetic Field Laboratory, MPI-FKF and CNRS, F-38042 Grenoble Cedex 9, France*

Received 13 August 2002

Abstract

The direction of easy magnetisation in molecular beam epitaxy grown (1 1 0) films of $DyFe_2$ is known to change from [0 0 1] at low temperatures to close to $[\bar{3}\,5\,1]$ at room temperature. In this paper we present compelling anisotropic magneto-resistance measurements for the presence of a meta-stable magnetic state aligned along the $[\bar{1}\,1\,0]$ axis at 100 K.

Keywords: Epitaxy; Rare-earth transition metal; Anisotropic magneto-resistance; Thin magnetic films

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1. Introduction

In recent years, thin films of the cubic rare-earth iron compounds $REFe_2$, grown using molecular beam epitaxy (MBE) on sapphire substrates, have been studied by ^{57}Fe Mössbauer spectroscopy [1,2], magnetometry and the magneto-optic Kerr effect [2,3], and more recently by vector vibrating sample magnetometry [4]. At low temperatures the magnetisation lies along the [0 0 1] axis, in the plane of the (1 1 0) film. But at temperatures of about 100 K, the direction of magnetisation changes and at room temperature appears to lie near the $[\bar{3}\,5\,1]$ or the $[\bar{3}\,5\,0]$ axis [2,4]. The underlying reason for this behaviour has been attributed to the presence of a magneto-elastic strain term, induced during crystal growth. In bulk $DyFe_2$ the direction of magnetisation is determined by the single-ion crystal fields at the Dy^{3+} sites, which favour the [0 0 1] or equivalent axis at all temperatures [5]. However, in MBE-grown films there is an additional magneto-elastic strain term which favours an in plane $[\bar{1}\,1\,0]$ direction [2]. Thus, there is competition between the single ion crystal field and magneto-elastic terms in determining the direction of easy magnetisation.

In this paper we report anisotropic magneto-resistance (AMR) measurements on MBE-grown $DyFe_2$ films, performed at the Grenoble High Magnetic Field Laboratory. The results show that it is possible to use AMR measurements to study the meta-stable states in magnetic thin films. In

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*Corresponding author. Tel.: +23-8059-3599; fax: +23-8059-3910.

E-mail address: gjb@phys.soton.ac.uk (G.J. Bowden).

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PII: S0304-8853(02)01208-8

particular, compelling AMR evidence is presented for the presence of a meta-stable state in $DyFe_2$ aligned along the $[\bar{1}\,1\,0]$ axis at 100 K.

2. Sample, growth and characterisation

The 4000 Å thick $DyFe_2$ film was grown by MBE techniques using the Balzers UMS 630 UHV facility at Oxford, following a procedure described in Ref. [1]. The samples were grown on epi-prepared $(1\,1\,\bar{2}\,0)$ sapphire substrates with a 100 Å (1 1 0) Nb buffer and a 20 Å layer of Fe. The Laves phase compound was synthesised by co-deposition of elemental fluxes at a substrate temperature of 400°C in (1 1 0) orientation, with the major axes parallel to those of niobium. $DyFe_2$ belongs to the cubic Laves space group O_h^7-F3dm $MgCu_2$ type, with bulk lattice parameters $a = 7.325$ Å [4]. Ex situ X-ray diffraction techniques were used to confirm the single-crystal nature of the film.

3. Anisotropic magneto-resistance measurements and sample alignment

The transport measurements were performed in fields up to 10 T using standard four-point techniques. In practice, the temperature had to be controlled to better than 0.1 K, to avoid additional changes in resistance caused by drifts in temperature. The transport insert used allowed the sample to be rotated through 90°, with both the current and the magnetic field in the plane of the film. The principle configurations studied in the experiments are shown schematically in Figs. 1(a) and (b).

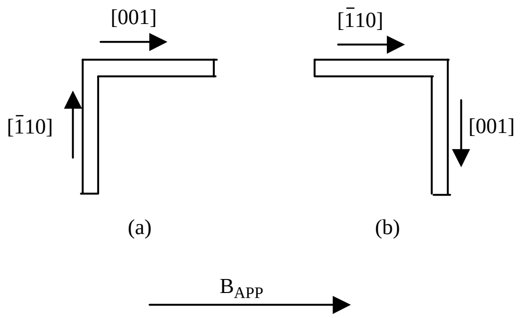

Fig. 1. Principle orientations of the $DyFe_2$ film, with respect to the applied field. The small arrows indicate the cubic axes in question and the direction of the currents.

Finally, all the measurements reported here were performed at 100 K. At this temperature, the magneto-resistance of the underlying Nb buffer layer can be neglected. Thus any change in the resistance of the film, caused by the application of the magnetic field, is due to the $DyFe_2$ film.

4. Results

The transport measurements, obtained using the configuration shown in Fig. 1(a), are summarised in Fig. 2. To avoid problems associated with sample geometry (rectangular shapes ~4 × 0.5 mm), the results are presented in terms of the dimensionless quantity:

$$\frac{\Delta\rho}{\rho} = \frac{\rho(B_{APP}) - \rho(B_{APP} = 0)}{\rho(B_{APP} = 0)}. \qquad (1)$$

Note that for the top curves in Fig. 2(a) $(\Delta\rho_\perp/\rho_\perp)$, both the $[\bar{1}\,1\,0]$ axis and current are perpendicular to B_{APP}, while for the bottom curves

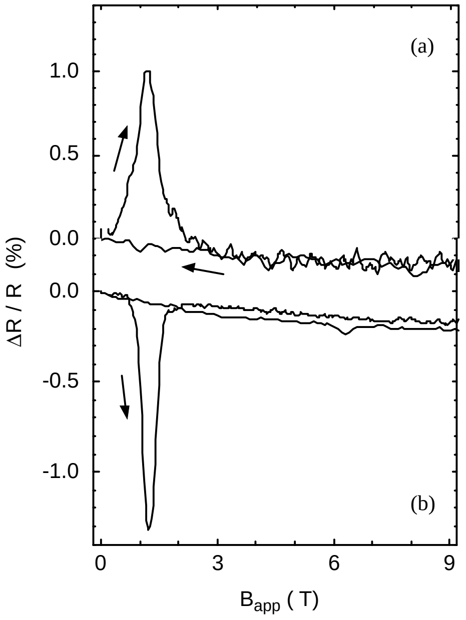

Fig. 2. $\Delta\rho_\perp/\rho_\perp$ (a) and $(\Delta\rho_\parallel/\rho_\parallel)$ (b) as a function of magnetic field for the geometry shown in Fig. 1(a).

($\Delta\rho_{\parallel}/\rho_{\parallel}$), both the [0 0 1] axis and current are parallel to the applied magnetic field B_{APP}. These curves can be interpreted as follows. Starting with the sample fully polarised in a negative field of $-10\,\mathrm{T}$, the field is swept from -10 to $+10\,\mathrm{T}$. When the field reaches the coercive field $B_{\mathrm{C}}=+1.2\,\mathrm{T}$, the $\mathrm{DyFe_2}$ moments reverse giving rise to classic AMR features [6,7]. Namely, a positive going excursion for ($\Delta\rho_{\perp}/\rho_{\perp}\sim 1\%$) accompanied by a negative peak in ($\Delta\rho_{\parallel}/\rho_{\parallel}\sim -1\%$). For AMR, these two peaks should be antisymmetric with each other [6,7]. However, it will be observed from an examination of Fig. 2 that the ($\Delta\rho_{\perp}/\rho_{\perp}$) peak is broader than that of the ($\Delta\rho_{\parallel}/\rho_{\parallel}$) peak, suggesting that the magnetic reversal ([0 0 1]$\rightarrow$[0 0 $\bar{1}$]) in the [$\bar{1}$ 1 0] leg is broader than that in the [0 0 1] leg. But to probe this point in more detail will require $M-H$ loops of the two legs in question investigated separately.

The transport measurements obtained using the configuration shown in Fig. 1(b) are summarised in Fig. 3. Here the two crystallographic axes have been reversed with respect to the applied field. So the [$\bar{1}$ 1 0] axis and current are now parallel to the applied magnetic field B_{APP}, while the [0 0 1] axis and current are perpendicular to B_{APP}. Rather surprisingly, very little in the way of AMR peaks can be seen when the field passes through the coercive field at $B_{\mathrm{C}}=1.2\,\mathrm{T}$. We believe that a full interpretation of this data will require a detailed knowledge of the domain wall structure during magnetic field reversal.

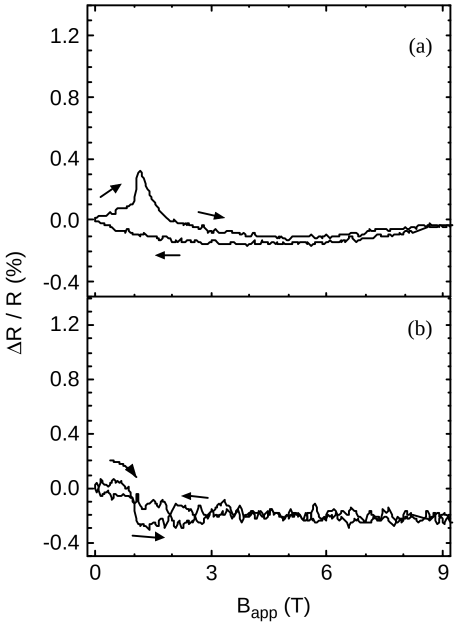

Fig. 3. $\Delta\rho_{\perp}/\rho_{\perp}$ (a) and ($\Delta\rho_{\parallel}/\rho_{\parallel}$) (b) as a function of magnetic field for the geometry shown in Fig. 1(b).

Finally, both Figs. 2 and 3 reveal that the resistances change very little on reducing the magnetic field from saturation back to zero field. This implies that the magnetisation remains uniform and does not break up into domains. For the [0 0 1] easy axis, this is not entirely unexpected. Magnetisation measurements have shown that $\mathrm{DyFe_2}$ is a hard magnet with a very square $M-B_{\mathrm{APP}}$ loop [3]. However, the AMR result for the [$\bar{1}$ 1 0] axis is surprising and suggests that this axis might be a meta-stable state.

Further support for this point of view can be gleaned from remanent resistance of the [0 0 1] leg in the two experiments summarised in Figs. 1(a) and (b). Despite having exactly the same geometry, the remanent resistances of the magnetically polarised [0 0 1] and [$\bar{1}$ 1 0] states were found to be different. This implies two differing remanent magnetic states. Thus, once again we have evidence for the possibility of a meta-stable magnetic state, corresponding to a local minima in the energy, along the [$\bar{1}$ 1 0] axis.

To illustrate this point still further, the following experiment was performed. First, the $\mathrm{DyFe_2}$ film was polarised along the [$\bar{1}$ 1 0] axis, using the configuration shown in Fig. 1(b). Secondly, the applied field was reduced to zero and the sample was rotated through 90° to the configuration shown in Fig. 1(a). Thus, the magnetisation and the [$\bar{1}$ 1 0] axis are now perpendicular to the direction of the applied field. Thirdly, the applied field was ramped from 0 to $10\,\mathrm{T}$ and subsequently back to zero. During this phase of the experiment, therefore, the magnetisation should rotate from the nominally 'hard' [$\bar{1}$ 1 0] axis to the nominally 'easy' [0 0 1] axis, at least in high fields. The magneto-transport results are summarised in Fig. 4. It is immediately apparent that there are two distinct remanent resistances. We suggest that the initial and final resistances are those appropriate to the [$\bar{1}$ 1 0] and [0 0 1] directions of

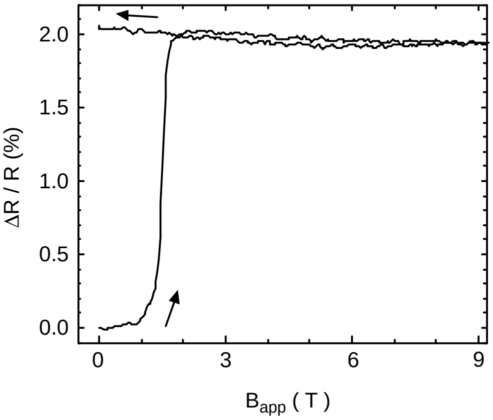

Fig. 4. Change in resistance of the [0 0 1] resistance leg $(\Delta\rho_{[0\,0\,1]}/\rho_{[0\,0\,1]})$ with the magnetisation initially along the [$\bar{1}$ 1 0] axis, but finally along the [0 0 1] axis.

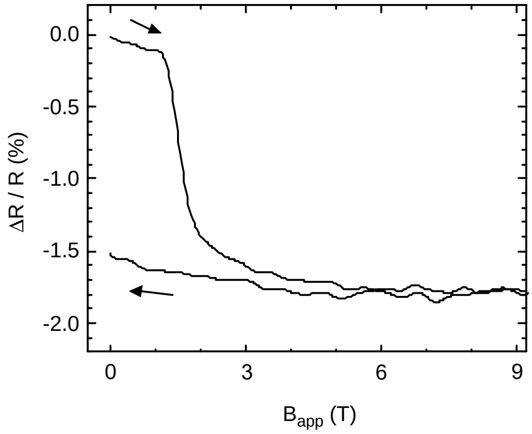

Fig. 5. Change in resistance of the [$\bar{1}$ 1 0] resistance leg $\Delta\rho_{[\bar{1}\,1\,0]}/\rho_{[\bar{1}\,1\,0]}$ with the magnetisation initially along the [$\bar{1}$ 1 0] axis, but finally along the [0 0 1] axis.

magnetisation, respectively. Note that (i) the rotation of the magnetisation takes place at about 1.5 T, (ii) the size of the AMR step amounts to ~2%, and (iii) this determination of the strength of the AMR effect is very 'clean', given the absence of domains walls in both the initial and final states.

A similar set of measurements for the [$\bar{1}$ 1 0] resistance leg can be seen in Fig. 5.

In summary, therefore, we conclude that the AMR results show that while the easy direction of $DyFe_2$ lies along the [0 0 1] axis at 100 K, there is a meta-stable state with an easy direction of magnetisation along the [$\bar{1}$ 1 0], or equivalent axis.

5. Discussion

We have shown that AMR measurements can be used to study meta-stable states in magnetic thin films. In particular, evidence has been presented for the existence of the [$\bar{1}$ 1 0] meta-stable magnetic state in MBE-grown $DyFe_2$ at 100 K. The latter supports the conjecture that strain induced during crystal growth introduces a magneto-elastic term which favours the [$\bar{1}$ 1 0] axis [2].

Acknowledgements

This work has been supported by the (i) the Advanced Magnetics Program of the EPSRC (ii) in part by QinetiQ Ltd, and (iii) the Human Potential Programme under Contract No. HPRI-1999-CT00030. We also like to acknowledge useful discussions with R. Cowley, M. Bentall, and G. Tomka.

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