

# Room temperature coercivities of $Tb_{1-x}Dy_xFe_2$ (110) molecular beam epitaxy grown films

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(Presented on 15 November 2002)

It has been known for many years that the rare-earth intermetallic compound terfenol ( $Tb_{0.3}Dy_{0.7}$ ) $Fe_2$  is characterized by “giant magnetostriction,” which has found practical applications. In this article we report the magnetic properties of a series of molecular beam epitaxially (MBE) grown (110)  $Tb_{1-x}Dy_xFe_2$  alloy films, on sapphire substrates. All the measurements were performed at room temperature with the field applied along an in-plane  $[\bar{1}10]$  axis. However, unlike bulk  $Tb_{1-x}Dy_xFe_2$ , it is shown that the coercivity does not fall to zero at the magic ratio of  $x \sim 0.7$ . Instead, the coercivities fall almost on a straight line, with the maximum coercivity for pure  $TbFe_2$  (0.64 T) and the smallest for  $DyFe_2$  (0.22 T). The difference between the bulk and MBE films is attributed to the presence of a magnetoelastic strain term, induced during crystal growth by the sapphire substrate. In practice, the measured coercivities can be described, approximately, with a modified Stoner–Wohlfarth model. © 2003 American Institute of Physics. [DOI: 10.1063/1.1540251]

## I. INTRODUCTION

Giant magnetostriction in bulk terfenol ( $Tb_{0.3}Dy_{0.7}$ ) $Fe_2$  has found many uses in practical applications (see, for example, Ref. 1). So it is possible that terfenol nano-structures may prove useful as transducers in microelectromechanical systems (MEMS).<sup>2</sup> However, in practice, two requirements must be satisfied. One, the magnetostriction must be large, and two, the coercivity must be small. In this article we report the magnetic properties of a series of  $Tb_{1-x}Dy_xFe_2$  alloy films, grown by molecular beam epitaxy (MBE) on sapphire substrates. The magnetic measurements were performed at room temperature with the field applied along an in-plane  $[\bar{1}10]$  axis. Measurements show that this is the “in plane” easy axis of magnetization, for all samples.

## II. SAMPLE, GROWTH, AND CHARACTERIZATION

The  $Tb_{1-x}Dy_xFe_2$  alloy films were grown by MBE techniques using the Balzers UMS 630 UHV facility at Oxford, following a procedure described in Ref. 3. The samples were grown on epitaxially prepared (11 $\bar{2}$ 0) sapphire substrates with a 100 Å (110) Nb buffer and a 20 Å layer of Fe. All the samples were 4000 Å thick. The Laves phase compounds were grown by codeposition of elemental fluxes at a substrate temperature of 400 °C in (110) orientation, with the major axes parallel to those of niobium. Both the compounds,  $DyFe_2$  and  $TbFe_2$ , belong to the cubic Laves space group  $O_h^7-F3dm$  MgCu<sub>2</sub>-type with bulk lattice parameters of  $a = 7.325$  and  $7.347$  Å, respectively.<sup>4</sup> So the lattice mismatch is expected to be minimal. *Ex situ* x-ray diffraction techniques were used to confirm the single crystal nature of the films.

## III. MAGNETIC MEASUREMENTS

All the magnetic measurements were performed at room temperature using an Oxford Instruments 12 T vibrating sample magnetometer, with the field applied along an  $[\bar{1}10]$  axis. Examples of hysteresis loops are given in Figs. 1(a)–1(c). From an examination of these figures it will be observed that the loops are square, which indicates that the applied field is either along or close to the easy axis.

## IV. DISCUSSION

From the magnetic point of view, both bulk  $DyFe_2$  and  $TbFe_2$  are characterized by high Curie temperatures  $\sim 600$  K, as a result of strong Fe–Fe ferromagnetic exchange (see reviews in Refs. 4 and 5). In both compounds the rare earth (RE) moments are coupled antiferromagnetically to those of the Fe, as a result of relatively strong RE–Fe exchange fields  $\sim 100$  T ( $\sim 100$  K). Finally, the direction of easy magnetization is controlled by (i) the single-ion crystal field interaction at the two RE sites,<sup>6</sup> and (ii) a magnetoelastic strain term  $E_{ME} = b_2 \epsilon_{XY} \alpha_X \alpha_Y$ .<sup>7</sup> In MBE-grown (110)  $TbFe_2$  films, <sup>57</sup>Fe–Mössbauer studies have been used to show that the direction of easy magnetization is  $[111]$  at all temperatures, while in  $DyFe_2$  the easy direction of magnetization is close to the  $[\bar{1}10]$  axis, at room temperature.<sup>7</sup> However, in contrast to the <sup>57</sup>Fe–Mössbauer results, our magnetic measurements on  $TbFe_2$  indicate that the easy “in-plane” magnetization lies close to the  $[\bar{1}10]$  axis. However, more detailed vector vibrating sample magnetometer results will be required to determine the “out of plane” magnetic component.

Given that the easy axis of magnetization in the  $Tb_{1-x}Dy_xFe_2$  series lies close to a common  $[\bar{1}10]$  axis, the

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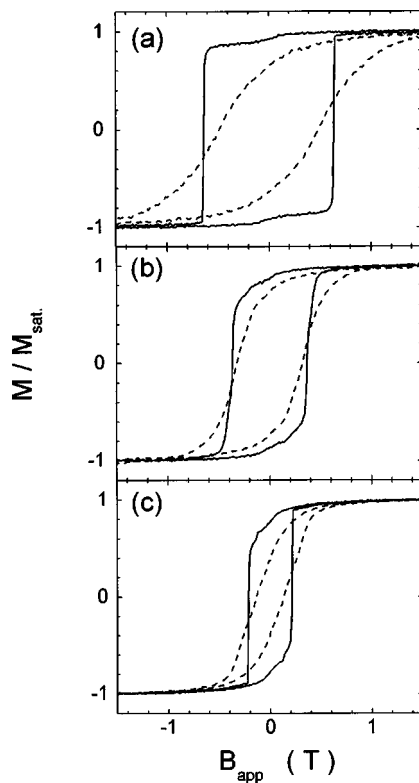


FIG. 1. Magnetic loops at 290 K of 4000 Å MBE film. (a)  $\text{TbFe}_2$  film ( $B_C = 0.64 \text{ T}$ ). (b)  $\text{Tb}_{0.5}\text{Dy}_{0.5}\text{Fe}_2$  ( $B_C = 0.39 \text{ T}$ ). (c)  $\text{DyFe}_2$  ( $B_C = 0.22 \text{ T}$ ). Key: Black (gray)  $B_{\text{app}}$  applied along the  $[110]$  ( $[001]$ ) axis, respectively.

Stoner–Wohlfarth model can be used to provide a simple explanation of the coercive field  $B_C$  as a function of  $x$ :

$$B_C(x) = \frac{2(K_{\text{Tb}}(1-x) + K_{\text{Dy}}x)}{(1-x)M_{\text{Tb}} + xM_{\text{Dy}}}, \quad (1)$$

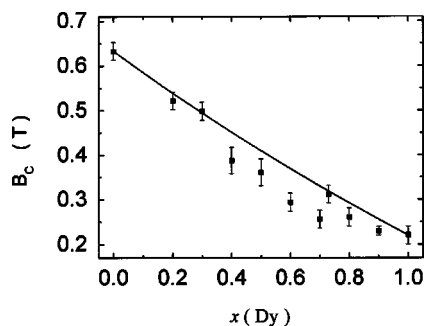


FIG. 2. The measured and theoretical coercivities as a function of Dy concentration  $x$ .

where (i)  $K_H$  ( $K_S$ ) is the anisotropy of the hard (soft) layer, (ii)  $M_H$  ( $M_S$ ) is the magnetic moment of the hard (soft) layer, and (iii)  $t_H$  ( $t_S$ ) is the thickness of the hard (soft) layer, respectively. In Fig. 2, the experimental points are compared with the predictions of Eq. (1). It will be observed that the majority of points fall below the Stoner–Wohlfarth prediction. These difficulties may be due to the “out of plane” magnetic components, alluded to earlier.

Three further points should be made. First, the sign of the  $b_2$  magnetoelastic term is the same for both  $\text{TbFe}_2$  and  $\text{DyFe}_2$ .<sup>7</sup> So if the magnetoelastic term is dominant at room temperature, this provides a natural explanation for the easy  $[\bar{1}10]$  magnetic axis for the entire  $\text{Tb}_{1-x}\text{Dy}_x\text{Fe}_2$  series. Second, the strength of the  $b_2$  term in  $\text{TbFe}_2$  is  $\sim 2$  times that of  $\text{DyFe}_2$ .<sup>7</sup> Thus the magnitude of the coercive field for  $\text{TbFe}_2$  should be about twice that of  $\text{DyFe}_2$ . In practice, the experimental ratio is found to be  $\sim 2.9$ . Third, it has been argued, on the basis of  $^{57}\text{Fe}$  Mössbauer results,<sup>7</sup> that the  $[111]$  axis is the easy axis of magnetization at all temperatures. However, given the presence of the magnetoelastic strain term this cannot be the case.

## V. CONCLUSIONS

The magnetic properties of MBE grown  $[011]$   $\text{Tb}_{1-x}\text{Dy}_x\text{Fe}_2$  alloys have been determined for fields applied along a  $[\bar{1}10]$  in plane axis. Unlike bulk terfenol, it appears that there is no magic ratio of  $x$ , at which the coercivity of the alloy film approaches zero. The underlying reason for this difference has been attributed to the presence of a magnetoelastic strain term in the MBE grown films, which favors the  $[\bar{1}10]$  axis. A simple Stoner–Wohlfarth model has been adapted to describe the variation of the coercive field as a function of  $x$ . However, a more detailed study of the direction of easy magnetization, including out of plane components, is required.

## ACKNOWLEDGMENTS

This work has been supported by the Advanced Magnetism Program of the EPSRC and funded, in part, by QinetiQ (formerly DERA Farnborough).

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