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Magnetostriction of Fe/Gd multilayers

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Abstract

Using strain-modulated ferromagnetic resonance method we have measured the magnetostriction constant λ_s of Fe/Gd multilayers deposited using rf and dc sputtering. For the samples deposited using rf sputtering the contribution to the effective magnetostriction due to the interdiffusion layers has been observed. Samples grown using dc sputtering are characterized by sharp interfaces with no indication of interdiffusion. In this case the magnetostriction consists of two components: one due to the bulk magnetostriction and another due to the intrinsic surface magnetostriction.

1. Introduction

In previous papers (see Refs. [1,2] for details and references) we reported first observations of surface magnetostriction in Fe- and Co-based multilayers. It has been shown that the magnetostriction in these multilayers can be mainly attributed to the dipolar interactions [3]. The magnetic dipolar mechanism also seems to be important for Gd-based multilayers. In contrast with all other rare earths gadolinium is a simple ferromagnet with an extraordinarily high Curie temperature of about 292.5 K [4]. It should also be mentioned that for this material the magnetic surface ordering was observed with a critical temperature of about 315 K.

Up to now, no investigations of magnetostriction of Gd thin films or multilayers have been performed. In this paper we present first measurements of magnetostriction of Gd/Fe multilayers. These multilayers are of some interest because of their behaviour as 'giant ferrimagnets', discovered by Kamiguchi et al. [6]. This means that the magnetization in Fe and Gd layers is aligned in antiparallel due to the antiferromagnetic exchange interactions between Fe and Gd magnetic moments. For such materials a new type of magnetoresistance was observed [7].

2. Experimental details

The Fe/Gd multilayers were prepared by two methods. For series A, B and C (see Table 1) sequential rf sputtering was used with a system that was first pumped to a pressure of 4×10^{-7} Torr. The targets were pure Fe (99.999%) and Gd (99.95%). The deposition parameters were rf power 80 W and argon pressure 6 mTorr. Water-cooled glass substrates were used during deposition. The

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Table 1
The experimental data of magnetostriction constant of Fe/Gd multilayers for different sublayer thicknesses (n = number of bilayers, M_s = magnetization of the multilayer).

Series	t_{Fe} (nm)	t_{Gd} (nm)	n	M_s (G)	λ_s ($\times 10^6$)
A	40	40	3	1470	−1.1
	20	20	6	910	−2.3
	10	10	12	1040	−2.3
	5	5	24	800	
B	40	40	3		−1.6
	20	20	6	1210	−1.9
	10	10	12	1150	−2.7
	5	5	24	1055	−1.7
C	14	40	3	840	+0.2
	7	20	6	800	−0.4
	3.5	10	12	550	0
	1.7	5	24	300	+0.3
D	10	10	10	740	−5.4
	4	4	20	730	−4.0
	2	2	40	740	−1.33

deposition rate was measured with a quartz crystal monitor. A check was made for Fe by measuring also the magnetization on a single thick layer. For series D sequential dc sputtering with a high argon pressure of 2.5×10^{-1} Torr was used. The high argon pressure makes the energy of the atoms arising at the substrate sufficiently low and hence favours a homogeneous layer thickness and a sharp interface. As substrates, single-crystal plates of GaAs with orientation (001) were used. The temperature of the substrates was 85°C.

The saturation magnetization and hysteresis loops of the films were measured by a vibrating sample magnetometer with an applied field up to 15 kOe, at 4.2 K and at room temperature.

The magnetostriction constants were measured at room temperature by the strain-modulated ferromagnetic resonance (SMFMR) method [8] at 9.10 GHz with an external magnetic field and uniaxial stress parallel to the film plane and perpendicular to each other. In the SMFMR technique the strain, periodic in time, causes a modulation of the ferromagnetic resonance (FMR) line position. To obtain the values of the components of the magnetoelastic tensor one should compare the intensity of the SMFMR line with the intensity of the same line detected using the standard FMR technique.

In addition to obtaining information on the magnetostriction constants, the SMFMR technique offers the opportunity to study the interface effects (including interdiffusion mixing); in particular it can be used to separate the intrinsic surface magnetostriction from the interface-induced effects. To perform such separation one should get information concerning the anisotropy of the magnetoelastic tensor [9]. Generally speaking, SMFMR is a unique technique that allows the possibility of measuring more than one component of the magnetoelastic tensor.

In the case of Fe/Gd multilayers we have not been able to apply the procedure proposed in Ref. [9]. In spite of that, we estimated the magnetostriction of the iron, gadolinium and the interdiffusion layer using the SMFMR technique. Moreover, for series D we succeeded in measuring the surface magnetostriction.

3. Results and discussion

Typical FMR and SMFMR spectra for the samples prepared by rf sputtering with $t_{Fe} = 20$ and 5 nm are shown in Figs. 1 and 2. For sublayers with $t_{Fe} = 20$ nm the measured lines are symmetric and similar to those observed in our previous studies [10]. A completely different picture was observed for sublayers with $t_{Fe} = 5$ nm. It can be seen from Fig. 2 that in this case the measured lineshape obtained using the SMFMR technique is quite different from that obtained by the FMR method. The unusual shape of the SMFMR line indicates that it comes from the superposition of two lines being very close in the parallel field configuration and having opposite polarization. The opposite polarization of these lines results from the different signs of the magnetostriction constants of magnetic layers, creating resonance lines. For the extreme case of two lines with the same resonance field but with opposite polarization, one should expect that the intensity of the SMFMR line will be strongly reduced yielding wrong information about the magnetostriction constants. We have therefore carefully analyzed the FMR and SMFMR spectra, decomposing them into two lines in order to obtain correct information about the

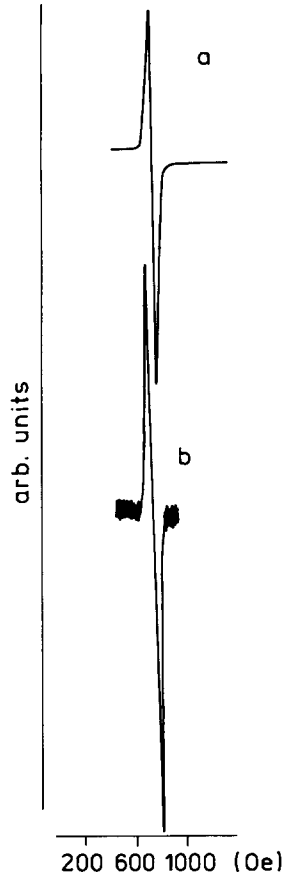

Fig. 1. FMR (a) and SMFMR (b) spectra of the Fe/Gd multilayer with thickness $t_{Fe} = 20$ nm and $t_{Gd} = 20$ nm.

intensity of the individual lines. This attribution is crucial for the interpretation of our experimental data. In order to obtain further proof of our interpretation we investigated several samples (see Table 1) with various thicknesses of Fe and Gd sublayers (but probably with the same interdiffusion layer thickness). Careful analysis of the intensity of the decomposed lines confirms the proposed interpretation. The results of these measurements are summarized in Table 1.

Assuming that the magnetostriction of the total multilayer is determined by the balance in magnetostriction among the Fe, Gd and interdiffusion layers, the effective magnetostriction constant, λ_s, can be expressed by the equation [11]:

$$\lambda_s = (1/(t_{Fe} + t_{Gd}))\{\lambda_{Fe} t_{Fe} + \lambda_{Gd} t_{Gd} + t_x(2\lambda_x - \lambda_{Fe} - \lambda_{Gd})\}, \quad (1)$$

where t_{Fe} and t_{Gd} are the programmed Fe and Gd layer thicknesses, respectively, t_x is the thickness of interdiffusion layer, λ_s is the measured magnetostriction of the total film, and λ_x is the estimated value for the interdiffusion layer. For series A and B λ_x is assumed to be equal to 4×10^{-6} [12], and for series C to be equal to zero because for series A and B the interface is expected to be an amorphous alloy with composition $Gd_{25}Fe_{75}$ [13], while for series C the interface has the composition $Gd_{50}Fe_{50}$ (this alloy is paramagnetic at room temperature). In both cases the chemical composition of the interface was determined [13] by means of the Mössbauer technique [14] (see, for example, Figs. 3 and 4). It was also assumed, in accordance with experimental data [13], that the thickness of the FeGd interdiffusion layer is $t_x \approx 0.8$ nm. For λ_{Fe} the value -7×10^{-6} [8] is used. The λ_{Gd} value is estimated from Eq. (1). With this assumption the estimated value of magnetostric-

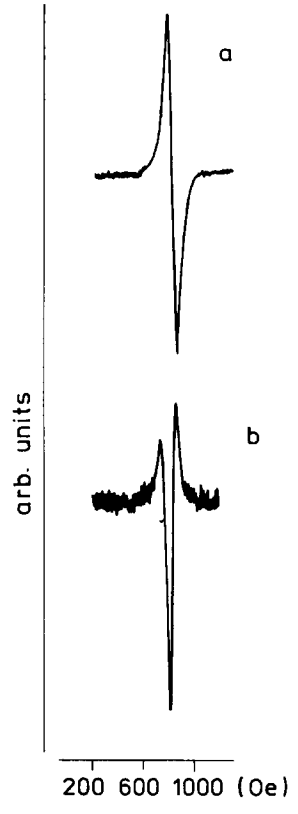

Fig. 2. FMR (a) and SMFMR (b) spectra of the Fe/Gd multilayer with thickness $t_{Fe} = 5$ nm and $t_{Gd} = 5$ nm.

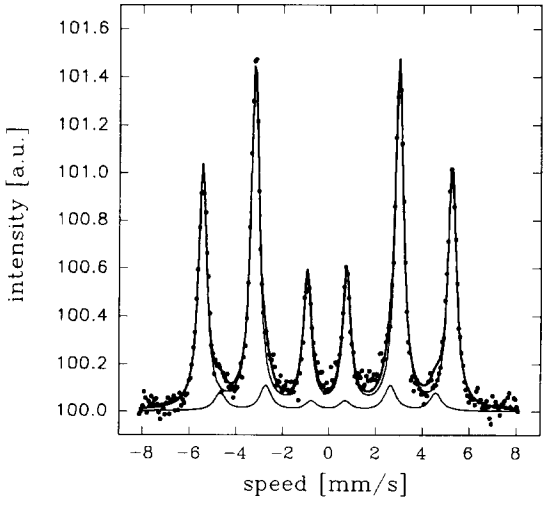

Fig. 3. Room-temperature Mössbauer spectra of the Fe/Gd multilayer with thickness $t_{Fe} = 5$ nm and $t_{Gd} = 5$ nm. The dots represent the experimental data and the solid lines the computer-fitted subspectra: bcc Fe (91.6% volume, hyperfine field = 332.5 kOe and amorphous $Fe_{0.75}Gd_{0.25}$ (8.4% volume, hyperfine field = 283.2 kOe).

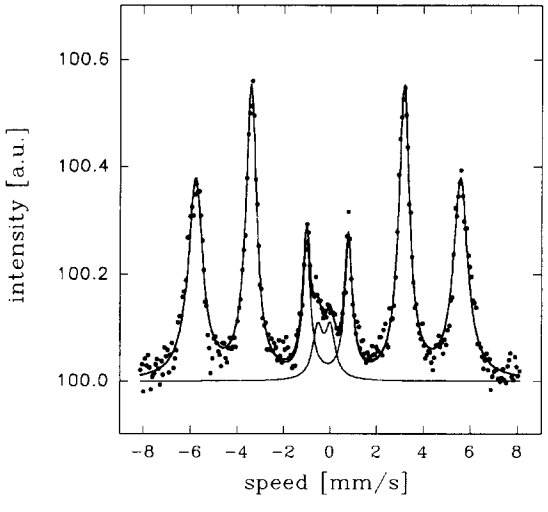

Fig. 4. Room-temperature Mössbauer spectra of the Fe/Gd multilayer with thickness $t_{Fe} = 14$ nm and $t_{Gd} = 40$ nm. The dots represent the experimental data and the solid lines the computer-fitted subspectra: bcc Fe (92% volume, hyperfine field = 334 kOe) and paramagnetic phase (8% volume).

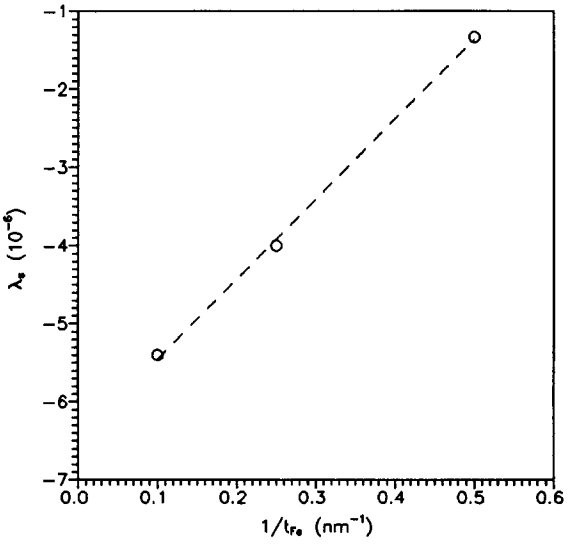

Fig. 5. Magnetostriction constant λ_s versus inverse iron layer thickness for series D.

tion for the Gd layer in series A, B and C is equal to 2×10^{-6}. This value is similar to that observed for bulk Gd [15], confirming the presented interpretation concerning the interdiffusion layers. In the case of samples of series D the situation is different. These samples were prepared by dc sputtering, yielding samples of high quality. FMR linewidths for series D are considerably narrowed in comparison with those observed for series A, B and C. The FMR and SMFMR measurements indicate only the presence Fe and Gd lines without any lines related to the interdiffusion layers. Probably for series D the interface is very sharp. In this case the effective magnetostriction, λ_s, is determined by the magnetostriction of Fe and Gd sublayers as well as by surface magnetostriction λ^s:

$$\lambda_s = (\lambda_{Fe} t_{Fe} + \lambda_{Gd} t_{Gd} + 2\lambda^s)/(t_{Fe} + t_{Gd}) \qquad (2)$$

In order to check this relation we display in Fig. 5 the effective magnetostriction as a function of t_{Fe}^{-1}. Since for series D we have $t_{Fe} = t_{Gd}$, Eq. (2) could be written in the form:

$$\lambda_s = \tfrac{1}{2}(\lambda_{Fe} + \lambda_{Gd}) + \lambda^s t_{Fe}^{-1}. \qquad (3)$$

The experimental data presented in Fig. 5 confirm

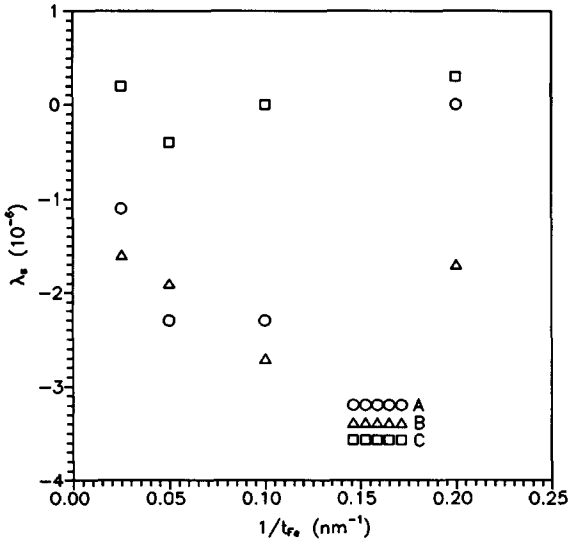

Fig. 6. Magnetostriction constant λ_s versus inverse iron layer thickness for series A, B and C.

the linear relationship between λ_s and t_{Fe}^{-1}. Using Eq. (3) one can determine

$\lambda^s = 10.2 \times 10^{-6}$ nm and

$\frac{1}{2}(\lambda_{Fe} + \lambda_{Gd}) = -6.5 \times 10^{-6}$.

The volume magnetostriction in this case is determined mostly by the magnetostriction of the Fe sublayer λ_{Fe} [110] $\approx -10 \times 10^{-6}$ [16]. The value of λ^s is of the order expected for the dipolar mechanism of surface magnetostriction [3]. It should be stressed that for series A, B and C the dependence of λ_s on t_{Fe} has not been observed (Fig. 6).

4. Conclusion

It has been shown that the magnetostriction of Fe/Gd multilayers depends strongly on the method of film deposition. We have observed the existence of the interdiffusion layers for samples deposited using rf sputtering. In the case of samples deposited using dc sputtering the interface was sharp. In this case we have observed the presence of surface magnetostriction strains localized at the interface between Fe and Gd sublayers.

Acknowledgement

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