FMR MEASUREMENTS ON CoCr/NiFe DOUBLE LAYERS

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Abstract

CoCr/NiFe double layers were measured by FMR for different angles of the applied field. Several resonance curves were observed for CoCr, which are attributed to the different layers of a magnetically stratified CoCr. This was investigated by carrying out FMR measurements on a single CoCr sample and removing successive layers by ion beam milling. The origin of some of the curves is still unclear. One resonance curve is attributed to the top or bulk layer and another to the initial layer. Stress was discovered to have an important influence on the resonance peaks.

Introduction

A double layer medium consisting of a CoCr perpendicular anisotropy film with a soft magnetic NiFe film underneath was reported by Iwasaki et al. to have a high recording sensitivity [1]. In our previous paper [2] the interaction between the two layers was studied using ferromagnetic resonance (FMR) measurements performed at 9 GHz, which gave information on the NiFe of the double layer. For the NiFe of the double layer the resonance field $H_r(\beta)$ (where β is the angle between the applied field and the normal to the film) is approximately equal to that of a single NiFe film. The difference in the width at half height ΔH of the resonance curves is due to the bombardment of the NiFe layer by the plasma particles during the deposition of the CoCr on top of it. FMR is a unique tool for determining different types of anisotropy energies which can occur in magnetic films and which are due to crystalline structure, stress, disordered structure, chemical inhomogeneities etc. It is well known that the microstructure of deposited CoCr layers can be divided at least into a so called "initial layer" (IL), (the first CoCr layer to grow on the substrate) and the bulk or "top layer" (TL) which has a well orientated structure and is characterized by a positive anisotropy i.e. $K_1 > 1/2\mu_0 M_s^2$ (where K_1 is the first order crystal anisotropy constant, M_s the saturation magnetization and μ_0 the permeability in vacuum). The structure and the magnetic behaviour of both layers are different [3-6]. The first confirmation by FMR of positive anisotropy in a single CoCr layer was reported by Mitchell et al. [7], and further investigated in [8,9]. In most of their single CoCr layers they found two resonance peaks: one due to the perpendicular (positive) anisotropy and one due to the in plane (negative) anisotropy ($K_1 < 1/2\mu_0 M_s^2$), which can be associated with the TL and the IL. This is concluded from FMR measurements in combination with ion milling the sample from top to bottom. In [7] a peak for $K_1 = 1/2\mu_0 M_s^2$ is also reported. Our present paper reports FMR measurements carried out at 35 GHz where $H_r(\beta)$ of both CoCr and NiFe in the double layer was measured. In order to obtain information on the origin of the different peaks these measurements were also carried out on single CoCr layers before and after various etching steps.

Experimental Techniques

The NiFe was RF-sputtered on Si using a 82/18 at% alloy target. Sputtering parameters were: argon pressure (P_{ar}) = $2.5 \cdot 10^{-2}$ mbar, bias voltage = 0.1 kV, sputter voltage (V_{RF}) = 1.0 kV, target-substrate distance (d) = 38 mm. A magnet of field strength 7.5 kA/m was placed around the substrate holder during sputtering to introduce a magnetic anisotropy. The thickness (t) of the NiFe layer was chosen at 500 nm as this is the optimal value for reading [10]. The CoCr layer was magnetron sputtered (on Si in the case of single layers or on the NiFe in the case of double layers), using a 81/19 at% alloy target using the following sputter parameters: $P_{ar} = 6 \cdot 10^{-3}$ mbar, $V_{RF} = 200$ V, $d = 32$ mm. For both cases a Leybold Heraeus Z400 was used and the background pressure was less than $3 \cdot 10^{-7}$ mbar. Some samples were etched by ion beam milling. The etch rate was 6.5 nm/min, the power was 6.3 W and $P_{ar} = 2 \cdot 10^{-4}$ mbar. The sample was rotated to avoid anisotropic etching effects. The composition and thickness of the samples was checked using X-ray fluorescence. The first order anisotropy constant K_{1TH} was measured using a torque magnetometer (TM). Other magnetic parameters were obtained using a vibrating sample magnetometer.

The FMR apparatus contained a magnet producing a maximum DC field of 1590 kA/m (20 KOe). The resonance frequency $\omega/2\pi$ was 34.8 GHz. The sample was placed in the centre of a cylindrical cavity, resonating in the TE_{011} mode. The DC field could be rotated in a plane perpendicular to the RF field.

Theory

By solving the Landau-Lifshitz equation of motion (1) $H_r(\beta)$ can be determined theoretically [11].

$$\frac{d\vec{M}}{dt} = -\gamma (\vec{M} \times \vec{H}) \quad (1)$$

where γ is the gyromagnetic ratio, $\vec{M}$ the magnetization and $\vec{H}$ the field. The solution may be expressed in terms of the second derivatives of the free energy F .

$$\omega = \frac{\gamma}{M_s \sin \theta} (F_{\theta\theta} F_{\phi\phi} - F_{\phi\theta}^2)^{1/2} \quad (2)$$

where θ is the angle between $\vec{M}$ and the normal to the film, and ϕ the angle between $\vec{M}$ and a plane normal to the film, and $M_s = |\vec{M}|$. The values for $H_r(\beta)$ for NiFe were calculated in this way, as in [2]. For CoCr the free energy may be written as

$$F = 1/2 \mu_0 M_s^2 \cos^2 \theta + K_1 \sin^2 \theta - \mu_0 \vec{H}_r \cdot \vec{M} \quad (3)$$

Imposing the equilibrium conditions $F_\theta = F_\phi = 0$ and using $Q = 2K_1/\mu_0 M_s^2$ one obtains a relation between θ and H_r .

$$M_s (Q - 1) \sin 2\theta = 2H_r \sin (\beta - \theta) \quad (4)$$

Substituting (3) in (2) we can obtain an implicit equation for H_r . However using a high field approximation we obtained the following:

$$H_r^2 = -M_s (Q - 1) H_r (3 \cos^2 \beta - 1) + \left[\frac{\omega}{\mu_0 \gamma} \right]^2 \quad (5)$$

This has the advantage that by plotting H_r^2 versus H_r ($3 \cos^2 \beta - 1$) the material parameter M_s ($Q - 1$) and γ can be obtained independently of one another. This enabled us to calculate K_1 and γ and therefore the g factor for the different layers in the CoCr. Solving [5] for H_r a theoretical curve $H_r(\beta)$ can then be calculated.

Results and Discussion

In table 1 the magnetic parameters calculated using (5) for the resonance curves of the different samples measured are shown. In this article the magnetic parameters are used to compare resonance curves of different films. For this purpose g is the most important parameter since it is the most accurate. K_1 is obtained from $M_s(Q-1)$ using the average value of M_s of the whole film and especially for Q approaching 1, K_1 is the less accurate parameter.

type of layer	curve number	γ 10^{11} Hz/T	g	$M_s(Q-1)$ 10^3 kA/m	K_1 10^5 J/m ³
single CoCr	1	2.04	2.31	-0.23	0.7
1360 nm	2	1.82	2.07	0	1.3
	3	1.97	2.23	0.08	1.6
	4	1.89	2.15	0.20	1.9
single CoCr	5	1.98	2.26	-0.28	0.5
370 nm	6	1.74	1.98	0	1.3
	7	1.92	2.19	0.16	1.8
	8	1.96	2.23	0.13	1.7
CoCr	9	1.67	1.91	0.25	2.1
1350 nm	10	1.77	2.01	0.09	1.6
	11	1.98	2.26	0.18	1.9
double layer					
NiFe	12	1.93	2.2	-	-
single CoCr	13	2.20	2.50	-0.28	0.5
1360 nm without substrate	14	1.97	2.24	0.06	1.5

Table 1. The values of the magnetic parameters calculated using [5] drawing the theoretical curves through the measured values of $H_r(\beta)$.

In figures 1-4 the measured values of H_r as a function of β and the corresponding theoretical curves (solid lines) calculated using (5) are shown. Figure 1 shows the measurements of $H_r(\beta)$ for a single CoCr layer with thickness $t = 1360$ nm, $K_{1TM} = 1.6 \cdot 10^5$ J/m³, saturation magnetization $M_s = 460$ kA/m, quality factor $Q = 1.3$, $M_s(Q-1) = 0.12 \cdot 10^3$ kA/m. Figure 2 shows $H_r(\beta)$ for a single CoCr layer with $t = 370$ nm, $K_{1TM} = 1.2 \cdot 10^5$ J/m³, $M_s = 460$ kA/m, $Q = 1.1$, $M_s(Q-1) = 0.046 \cdot 10^3$ kA/m. From figures 1 and 2 it is clear that the CoCr layer gives several resonance peaks. In [8,9] this is associated with the magnetic stratification of CoCr. Figures 1 and 2 are both of single CoCr layers and are very similar despite of the difference in thickness of the layers. Considering the figures and respective magnetic parameters we may compare curves 1 and 5, 2 and 6, 3 and 8, as well as 4 and 7. For curves 1 and 5 we see that $H_r(\beta)$ decreases with β . These curves therefore correspond to a $Q < 1$ i.e. negative anisotropy. Mitchell et al. [7] also found a resonance peak with negative anisotropy for a single CoCr layer on Si. Their value for $g = 2.14$ is somewhat

Fig.1 Experimental values of $H_r(\beta)$ and theoretical curves for a 1360 nm single CoCr layer.

lower than our values of g for curves 1 and 5 which are 2.31 and 2.28 respectively. We do not find that the same value of $g = 2.14$ can correspond to both peaks with positive and with negative anisotropy as in [7]. In curves 3, 4, 7, 8 we see that $H_r(\beta)$ increases with β and these curves therefore correspond to a $Q > 1$ i.e. positive anisotropy. In [7] a resonance peak is found with positive anisotropy and $g = 2.14$ which is similar to that of 4 and 7. A curve independent of β , that is, with $Q = 1$ is also found. In [7] a resonance peak with $Q = 1$ is found, with $g = 2.0$, which can compare with our values of $g = 1.98$ and $g = 2.07$. In [9] the single CoCr layer gave two resonance peaks which are associated with the IL and the TL.

Fig.2 Experimental values of $H_r(\beta)$ and theoretical curves for a 370 nm single CoCr layer.

Fig.3 Experimental values of $H_r(\beta)$ and theoretical curves for a double layer (1350 CoCr on 500 nm NiFe).

Figure 3 shows $H_r(\beta)$ of a double layer with 1350 nm CoCr on top of 500 nm NiFe. It shows the resonance curves of CoCr such as those which are shown in figure 1 with the NiFe resonance curve superimposed on it. The IL curve is not visible because of the NiFe curve. Curve 3 may be compared with 11, both having similar g factors. In order to investigate the origin of the peaks the 370 nm single CoCr layer was treated by ion beam milling. First we removed 10 nm from the top of the sample by ion beam milling. FMR measurements gave the same $H_r(\beta)$ as before ion milling. None of the peaks had disappeared. Therefore no evidence for a surface ferromagnetic layer as in [12] was found by us. However it could be that the ion milling process itself generates a new surface layer. After this a further 200 nm were removed leaving a CoCr layer with a thickness of 160 nm. After etching 210 nm in all, the intensity of the peaks of curves 7 and 8 compared to curve 5, had been considerably reduced (see fig. 4). These observations and the fact that $Q > 1$ indicates that the curves 3, 4, 7, 8 belong to the TL of the sample. Comparing the values of K_1 for the different layers of the single CoCr (see table 1) to the average K_{1TM} of the whole sample the following can be observed. The K_1 of the IL is considerably lower than K_{1TM} . Moreover K_{1TM} is generally lower than K_1 of the TL. This difference is more significant for the thinner sample where the volume of the IL forms a larger fraction of the volume of the entire sample.

Fig.4 Resonance peaks of a 370 nm single CoCr layer a) before and b) after removing 210 nm off the top. (The intensities of the TL should only be compared with the corresponding IL as the vertical scale is not the same in both cases).

Fig.5 Experimental values of $H_r(\beta)$ and theoretical curves for a 1360 nm single CoCr layer without substrate

In order to investigate the influence of stress on the CoCr the 1360 nm single CoCr sample was separated from the Si substrate and FMR measurements were carried out (fig 5).

As in figures 1 and 2 there is a curve, namely 13, with $Q < 1$. However there is only one curve, that is 14, with $Q > 1$. K_1 for curve 14 is about 20% lower than K_1 of curves 4 and 7 and 6% lower than K_1 of 3 and 8. It would seem that there are two parts which respond differently to stress. The $Q = 1$ curve is not visible as it may be situated in the slope of curve 14. We etched 20 nm from the bottom of this sample. The intensity of the peaks of curve 13 compared to curve 14 had decreased. These observations and the fact that $Q < 1$ indicate that curves 1 and 5 as well as 13 belong to the IL.

Conclusions

FMR measurements were performed on CoCr/NiFe double layers and on single CoCr layers. For CoCr several resonance curves $H_r(\beta)$ are observed, which are associated with different layers in CoCr. One of the resonance curves with $Q < 1$ is attributed to the IL while another with $Q > 1$ belongs to the TL. A curve with $Q = 1$ is also observed. For this and certain other curves the origin is still unclear. The measurements are analysed using a new high field approximation model which enables us to calculate the corresponding theoretical curves for $\beta = 0^\circ - 90^\circ$ and calculate the corresponding γ and M_s ($Q=1$) independently of one another. Stress also has an important influence on the resonance peaks. Differences between the resonance curves of single and double layers could also be partly due to the influence of this factor.

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