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MAGNETIC SUSCEPTIBILITY ANALYSIS IN Co/Pt MULTILAYERS

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In this paper we report a study of magnetic properties and magnetization reversal in Co/Pt multilayer thin films. We compared the results obtained by different techniques for characterisation of the magnetic properties of Co/Pt multilayers (an induction method using computerised data acquisition and torsion magnetometry) in order to correlate these properties with structural and morphological features. Multilayered Co/Pt films with periods of (1.3-6.5) nm were produced by electrodeposition on (100)-textured Pt foils and (100)-textured Cu foils with a 50 nm Pt buffer layer. The effective magnetic anisotropy per unit volume and the coercive field were found to depend both on the Co layer thickness (t_{Co}) and the Pt layer thickness (t_{Pt}). The susceptibility curves were analysed using the real-time Fast-Fourier-transform (FFT) method. In films with magnetic coupled layers and well-marked surface anisotropy, the AC susceptibility is connected with a series of harmonic components of AC magnetization induced by magnetic field. These peculiarities could be determined by the interaction between the moving domain wall and the local potential well formed by dynamic defects at interfaces. The Fast Fourier Transform (FFT) analysis of the susceptibility curves is proposed as a new technique for the study of multilayers.

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1. Introduction

During the last years, the magnetic thin films and multilayers are the object of many studies because of their possible applications for high-density storage and magneto-optic media. It is only recently that electrochemical ways of preparing magnetic multilayers have received increased attention [1 - 3]. This interest is motivated by potential applications and by the low cost of their fabrication in comparison to vapour deposition techniques. The magnetic properties of electrodeposited multilayers are influenced by the crystalline quality and the thickness of Co and Pt layers [4, 5]. Parameters such as interface anisotropy between layers (based on symmetry breaking at the interface) and structure play a role in the appearance of the perpendicular anisotropy as well as in the process of the magnetization reversal. The aim of this paper is to investigate the dependence of the anisotropy and the magnetization reversal process on the interface quality of Co/Pt multilayers. We address this problem from the point of view of magnetic measurements (coercive field, magnetic anisotropy, and susceptibility), and also of the microstructural data.

2. Experiment

The samples were prepared by electrodeposition as described in our previous papers [4, 5]. We used a single complex solution containing Co^2+ and Pt^{2+} ions and we switched the deposition potential between a value at which Co and Pt deposit and a value at which only Pt deposits. The Pt content of the ferromagnetic Co layers is limited by keeping very low the Pt^{2+} concentration in the electrolyte. Thus, a layer nominated as Co layer contains only 1.5 atomic percentage of Pt, as it was experimentally demonstrated by electron diffraction analysis of X-rays (EDAX) [5]. Co/Pt multilayers were electroplated on the surface of a disk-shaped cathode (22 mm in diameter) from (100)-textured polycrystalline copper foils covered with a 50 nm buffer layer of platinum.

Layered and crystallographic structures of films were examined both by small-angle and grazing incidence X-ray diffraction (XRD) analyses. The results presented in our previous works [4, 5] will be used here. The thickness of one period (Λ) was considered as a sum of the individual layer thickness $\Lambda = t_{Co} + t_{Pt}$. The deposition rates were calibrated carefully to obtain nominal thickness by applying a method described in Ref. [5, 6].

The magnetic properties of the films for various intensities of the external magnetic field were investigated at room temperature with *DC* and *AC* methods. The *DC* measurements were performed with a torsion magnetometer in fields up to 300 kA m^{-1}. The *AC* magnetic measurements were carried out with an induction Howling type equipment by applying an alternating longitudinal magnetic field (85.55 kA m^{-1}, sinusoidal-field excitation, 50 Hz). Two identical pick-up coils (one of them containing the magnetic sample) are used in series opposition to acquire the induced voltage. The curves (*dM*/*dt*) versus *t* were recorded by digital scope interfaced to computer. They are determined by the differential susceptibility of the sample (χ) and by the rate of change of field with time:

$$\frac{dM}{dt} = \left(\frac{dM}{dH}\right)\left(\frac{dH}{dt}\right) = \chi \cdot \frac{dH}{dt} \tag{1}$$

The (d*M*/d*t*) versus (*t*) curves were digitized (2048 sampling points), stored on disk and analysed using Fast Fourier Transform (FFT) method. The sampled points from the scope were converted to the frequency range, using a square window function, thus yielding a spectrum of discrete harmonics.

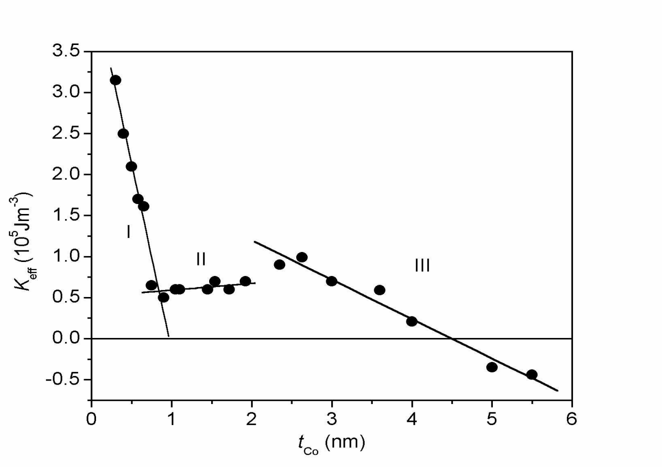

Fig. 1. Magnetic anisotropy constant K_{eff} as a function of nominal thickness of Co layer (t_{Co}) for a series of Co/Pt multilayers with t_{Pt} = 1 nm.

3. Results and discussion

In the case of electrodeposited Co/Pt multilayers by the present method, multilayer periodicity was observed by XRD only in the films with bilayer periods Λ thicker than 2.5 nm [4, 5]. Films with calculated period thinner than 2.5 nm consist in partially ordered alloys containing stoichiometric compounds of Co-Pt solid solution. It is known that these chemically ordered compounds are in fact composed from alternate stacks of the two type of atoms, therefore we can maintain for discussion the calculated periodicity and calculated Co and Pt layer thickness as work parameters.

Our preliminary results showed that the electrodeposited Co/Pt multilayers with t_{Pt} = 1 nm exhibit antiferromagnetic type coupling between Co layers. For this reason, a series of samples with fixed nominal Pt layer thickness (1 nm) and Co layer thickness varying from 0.3 nm to 5.5 nm were prepared. The total thickness of the films in this series was of about 100-170 nm.

We have found that the density of effective magnetic anisotropy energy K_{eff} (determined by torsion magnetometry) depends on the Co layer thickness t_{Co}. The dependence of K_{eff} as a function of t_{Co} for this series of samples is shown in Fig. 1. This curve could be separated in three regions (I, II and III), which were linearly fitted, corresponding to the three slopes of the straight lines.

It is known that any effective (or total) magnetic anisotropy constant for a thin film can be formerly separated into bulk and surface term [7]. In the case of multilayers, K_{eff} can be written:

$$K_{eff} = K_v + \frac{2K_s}{t_{Co}} \tag{2}$$

where K_v represents volume contributions and K_s (the surface or interface anisotropy) is the contribution for one surface [7, 8]. The term $K_v = -\mu_o M_s^2/2 + K_{mc} + K_{me}$ is a sum of all volume terms: magnetostatic energy, magnetocrystalline anisotropy (K_{mc}) and magneto-elastic anisotropy (K_{me}).

From the calculated slope ($-2K_s/t_{Co}^2$) of the three lines of Fig. 1, using equation 2, we have found the approximate values for surface anisotropy in these regions. The bulk term was calculated also ($K_v = K_{eff} - 2K_s/t_{Co}$). The following values were obtained.

In the first region, for t_{Co} < 0.75 nm we have calculated K_s=1×10^{-4} J m^{-2} and K_v~ 4×10^4 J m^{-3}. These samples are composed from crystalline grains of tetragonal face centered (tfc) *L10* CoPt or *L1*$_2$ $CoPt_3$ ordered phases of Co-Pt solid solution [4, 5].

In the third region, for t_{Co}>2.6 nm, one obtains K_s=5×10^{-4} J m^{-2} and K_v =-2×10^4 J m^{-3}. These multilayers are composed of hcp Co layers stacked with amorphous Pt layers [4, 5].

In the second region, for Co layer thickness between 2.6 nm and 0.75 nm, the estimated values are K_s~ 0, and K_v =+5×10^4 J m^{-3}. The films in this region have a heterogeneous transitional structure between structures of type III and I.

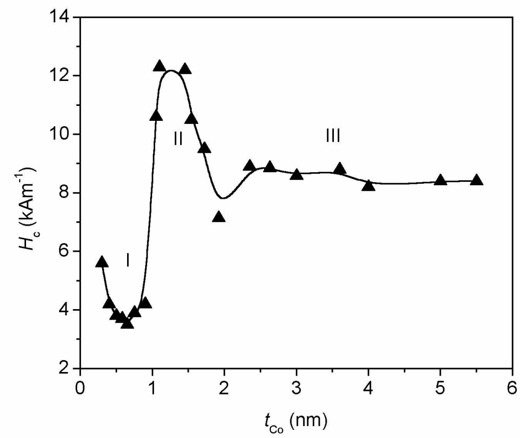

Fig. 2. Coercive field H_c as a function of t_{Co} for a series of Co/Pt multilayers with t_{Pt} = 1 nm.

Coercive field of the multilayers depends on the thickness of Co layer, for the series of samples with $t_{Pt} = 1$ nm, as it is shown in Fig.2. The three types of films (in the same Co thickness regions marked in Fig. 1) have different magnetic behaviour from the coercivity's point of view. The H_c takes a maximum value of about 12.3 kA m^{-1} for films with multiphase heterogeneous structure from the region 2.6 nm<t_{Co}< 0.75 nm. This behaviour could be explained in good accordance with ordinary mechanisms of coercivity (pinning and nucleation of domain walls). The films in the first region (i.e. the ordered alloys) show the lowest values of H_c and the heterogeneous films have the biggest ones.

The shape of magnetic susceptibility curves is different for samples pertaining to different regions, as could be seen for example in Fig. 3 for three typical samples: [0.3 nm Co/1.0 nm Pt]*126 (Fig. 3a), [1.1 nm Co/1.0 nm Pt]*55 (Fig. 3b) and [3.3 nm Co/1.0 nm Pt]*25 (Fig. 3c). One observes that: each curve has its specific shape and fine structure due to Barkhausen transitions in the magnetization reversal process.

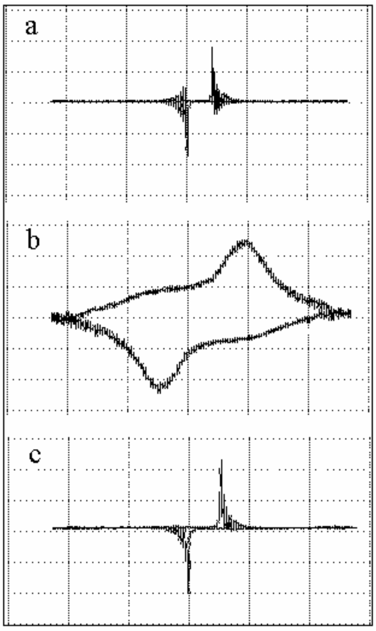

Fig. 3. Magnetic susceptibility curves for multilayers with t_{Pt} = 1 nm and nominal Co layer thickness of: 0.3 nm (a), 1.1 nm (b), 3.3 nm (c).

As an example of recorded curves in the Howling type device, typical curves for the three regions are shown in Fig. 4 for the following samples: [0.3 nm Co/1.0 nm Pt]*126 (Fig. 4a), [1.1 nm Co/1.0 nm Pt]*55 (Fig. 4b) and [4.0 nm Co/1.0 nm Pt]*25 (Fig .4c). In all these figures the notation of curves is the same: C1 - the output voltage of Y1-chanel, i.e. (dM/dt) vs. t) curve, C2 - the output voltage on Y2-chanel (H vs. t), C3- calculated FFT spectrum of the signal on Y1-chanel, and C4- integrated curve of the Y1-channel i.e. the unfold hysteresis loop. The X-axis for curves C1, C2 and C4 is in time range (maximum length of the scale is 10 ms). The X-axis for curve C3 (FFT spectrum) is in frequency range (between f = 0 and f = 24.90 kHz = ½ from the analyzed limit frequency).

From the shape of the curves in Fig. 4 one observes that: each differential hysteresis loop has its specific shape and the fine structure of each peak on curves C1 due to Barkhausen transitions or variations in domain-wall mobility is totally lost in the integrated curves (labelled C4). FFT curves (labelled C3) give the evidence of the high-order harmonic content of the differential hysteresis loop. All spectra for films of III and I type exhibit high-order frequency components (from 1 kHz to 34.5 kHz) with "clustering of impulses" in some frequency range specific for each sample. Both III and I type samples exhibit either a well-defined multilayer periodicity or superstructure, respectively, clearly evidenced by XRD measurements [4, 5]. The magnetic peculiarities of these samples are $Ks \neq 0$, antiferromagnetic type coupling between magnetic layers and out of plane magnetic anisotropy. In the case of B type samples ($Ks \cong 0$), only harmonic components with frequency lower than 1 kHz were observed (as in the ordinary samples of ferromagnetic materials studied in the same device and similar conditions).

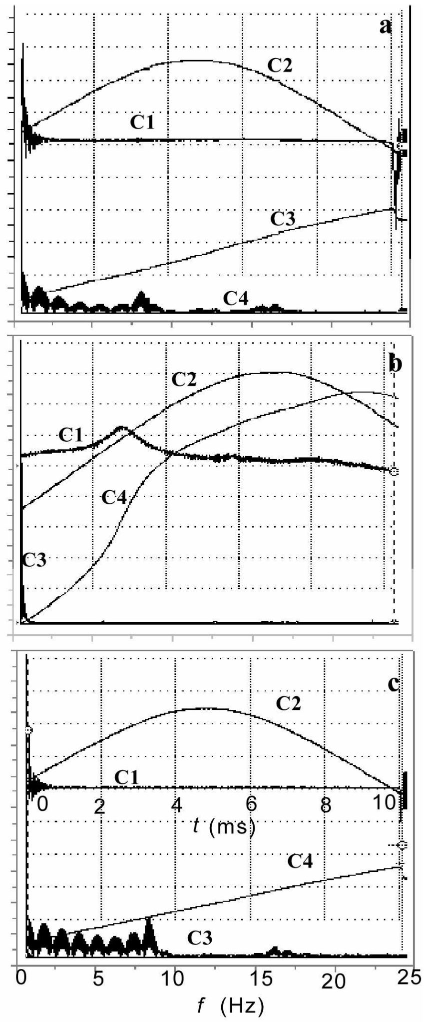

Fig. 4. Recorded data for multilayers: [0.3 nm Co/1.0 nm Pt]*126 (a), [1.1 nm Co/1.0 nm Pt]*55 (b) and [4.0 nm Co/1.0 nm Pt]*25 (c). The notation of curves is: C1 - (dM/dt) vs. t curve, C2 - the (H vs. t) curve, C3 - calculated FFT spectrum of C1 curve and C4- integrated curve of C1. The X-axis for curves 1, 2 and 4 is in the time range. The X-axis for curves 3 (FFT spectrum) is in frequency range. Y-axis scalation (in V/div): C1 = 5.00 (a), 0.200 (b), 1.00 (c); C2 = 2.00 (a, b, c); C3 = 0.100 (a), 0.020 (b), 0.050 (c); C4 = 0.001 (a), 0.100 (b), 0.0005 (c).

The observed behaviour may tentatively be explained by the effects of interface anisotropy and interlayer coupling on magnetization reversal. The AC susceptibility is connected with a series of harmonic components of AC magnetization induced by magnetic field. The temporal features of jump avalanches are correlated both with the geometrical features in multilayers (i. e. with number, quality and nature of interfaces), and with the type (and strength) of interlayer coupling. Due to the spatial periodicity of the magnetic layers distribution, a supplementary periodicity of the signal is created in the time (or frequency) scale. This periodicity is evidenced by FFT analysis of the harmonic content of the induced signal. The clustering of signals in some frequency domains could be similar with “standing waves” in magnetization reversal [10]. The nodes of the standing wave are spatially fixed by interfaces between magnetic and nonmagnetic layers. The susceptibility signal occurs due to fast rotations of spins (in the frequency range of ferromagnetic resonance or spin wave resonance) or, in the present work, due to the motion of domain walls triggered by the AC field. Obviously, ferro- or antiferromagnetic coupling centres influence free rotations of spins and the motion of domain walls.

The nonlinearities in susceptibility curve with respect to the AC magnetic field could be determined by the interaction between the moving domain wall and the local potential well formed by dynamic defects at interfaces. A quantitative interpretation is in progress.

4. Conclusions

The FFT method of analysis of (d*M*/d*t* vs. *t*) curves revealed significant differences between multilayered samples with $Ks \neq 0$ and films with incoherent growth and $Ks = 0$. This method is proposed as a tool for evidencing the interface quality in multilayered samples with out of plane anisotropy.

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