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Tuning the structure and magnetic softness of thin permalloy films by variations in the thickness of titanium seed layer

A.V. Svalov [a,b,*], G.V. Kurlyandskaya [a,b], B. González Asensio [a], J.M. Collantes [a], A. Larrañaga [c]

[a] Departamento de Electricidad y Electrónica, Universidad del País Vasco (UPV/EHU), 48080 Bilbao, Spain
[b] Department of Magnetism and Magnetic Nanomaterials, Ural Federal University, 620002 Ekaterinburg, Russia
[c] SGIker, Servicios Generales de Investigación, Universidad del País Vasco (UPV/EHU), 48080 Bilbao, Spain

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ABSTRACT

The role of the Ti seed layer thickness on the structural and magnetic properties of $Fe_{19}Ni_{81}$ thin films was studied. The samples were grown by a sputtering deposition technique on glass substrates at room temperature. The Ti cubic phase transforms into the hexagonal phase with the increase of the Ti layer thickness. Thin Ti seed layer plays very important role in the structure formation of FeNi films with good crystallinity and magnetic softness.

1. Introduction

The properties of sputtered magnetic thin films and multilayered structures can be dramatically improved through deposition onto appropriate seed or buffer layers [1]. Most often the seed layer influences the magnetic properties through a change in the film structure. For example, it happens in multilayered structures with exchange bias where the Cu seed layer induces the growth of an antiferromagnetic face-centered-cubic FeMn layer with a [111] orientation [2]. Another possible reason for the significant improvements in the crystallinity and texture of magnetic films deposited on seed layers can be explained by surface energy and kinetic effects. Due to the large surface energy of the seed layer, the magnetic film forms two-dimensional flat islands with any preferred orientation at the initial stage. Then the oriented islands impinge on each other and a highly textured polycrystalline film forms [3]. Recently it was shown that a Ti seed layer can improve the structural features of neighbor films resulting in the development of a strong texture and larger grain size [4,5]. However, the origin of the effect of the Ti seed layer on the film structure and the resulting effect on the magnetic properties is not entirely understood. In this study, we concentrated on the influence of the thickness of the Ti seed layer on the structure and magnetic properties of FeNi soft magnetic films.

2. Experimental procedure

The samples were deposited by magnetron sputtering onto glass substrates at room temperature. Background pressure was 3×10^{-7} mbar and the argon pressure during deposition was 3.8×10^{-3} mbar. Permalloy layers were deposited using a $Fe_{19}Ni_{81}$ target. A magnetic field of 250 Oe was applied during sample preparation parallel to the substrate surface in order to induce a uniaxial magnetic anisotropy. The deposition rates were 26 nm/min for FeNi layers and 4 nm/min for Ti layers. Standard X-ray diffraction (XRD) measurements were obtained using a PHILIPS X'PERT PRO automatic diffractometer operating at 40 kV and 40 mA, in theta–theta configuration, secondary monochromator with Cu-Kα radiation ($\lambda = 1.5418$ Å) and a PIXcel solid state detector (active length in 2θ 3.347°). Data were collected from 4° to 80° 2θ (step size = 0.026 and time per step = 300 s, total time 1 h) at RT. A fixed divergence and antiscattering slit giving a constant volume of sample illumination were used. The information from broadened XRD lines was used to estimate the average size of coherent diffraction domains by using the standard Scherrer approach.

For different (*hkl*) analysis a Bruker D8 Discover diffractometer was used. The instrument was equipped with a Cr Twist tube, Ni filter ($\lambda = 2.2911$ Å), PolyCap™ (1 μ single crystal cylinders) system for parallel beam generation (divergence of 0.25°), and a 1-D LynxEye detector (active length in 2θ 2.7°). The sample was

* Corresponding author at: Departamento de Electricidad y Electrónica, Universidad del País Vasco (UPV/EHU), 48080 Bilbao, Spain. Tel.: +34 946013237.
E-mail addresses: andrey.svalov@ehu.es (A.V. Svalov), galina@we.lc.ehu.es (G.V. Kurlyandskaya), beglezas@gmail.com (B. González Asensio), juanmari.collantes@ehu.es (J.M. Collantes), aitor.larranaga@ehu.es (A. Larrañaga).

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mounted on an Eulerian Cradle with automatically controlled *X*–*Y*–*Z* stage. Diffraction data were collected from 40 to 155 and 60 to 120 in 2θ (using a 1D mode for the detector and time per step of 1 s and 11 s each 0.05°) for short (20 h) and long (100 h) measurements, respectively. The data collection was done with Phi (φ) as spinner full circle 0–360. 1200°/min. speed, measuring from 0° to 75° with incr. of 5° in Psi (ψ).

The in-plane magnetic hysteresis loops were recorded by means of the magnetooptical Kerr effect (MOKE).

3. Results and discussion

Fig. 1 shows XRD spectra for three kinds of samples: FeNi (100 nm) film deposited directly onto glass substrate, Ti (10 nm)/FeNi (100 nm) and Ti (100 nm)/FeNi (100 nm) bilayers also deposited onto glass substrates. The main common feature observed in all samples is the intensive maximum at $2\theta \approx 44°$ position. This is the consequence of preferential crystal growth and the corresponding orientation of the (111) planes of fcc FeNi.

The crystallite size was 15 nm for the FeNi single layered film and about 35 nm for both bilayers. The FeNi film grown directly on glass shows a relatively weak (111) peak, which indicates a poor crystallinity or/and a poor texture. On the other hand, for the FeNi film grown on a Ti (10 nm) seed layer the intensity of this peak was several times higher. In comparison to this intense peak, the FeNi (200) peak at $2\theta \approx 52°$ was barely visible. This indicates that this FeNi film deposited onto a Ti seed layer has both very good crystallinity and high texturing. However, for Ti (100 nm)/FeNi sample an increase in the intensity of (111) peak was much smaller. In addition, for this bilayer, there is another intensive diffraction peak at $2\theta \approx 38°$. This peak can be identified as the (111) peak of fcc Ti, (110) peak of bcc Ti or (002) peak of hcp Ti [6]. In general, hcp is the stable phase of bulk Ti at room temperature. However, for very thin Ti films cubic phases can appear, which are energetically preferred in comparison with the hcp phase [7].

The typical XRD pattern for bcc Ti has only one intensive line with 2θ position at 38.5° [6]. Furthermore, metals growing incoherently on the substrates are known to acquire a close-packed structure, fcc (111) orientation [8]. In our case, the Ti/FeNi bilayers are assumed to have fcc structure, the Ti (200) peak in XRD pattern is located at nearly the same position of FeNi (111) large peak and it is therefore hidden behind one of its shoulders. Therefore it is not clear whether the Ti seed layers have fcc structure or not. In favor of the presence of hcp phase in the sample peaks the presence of a small (100) peak of hcp Ti at $2\theta = 35.5°$ (Fig. 1, inset).

Fig. 2 shows the X-ray diffraction of the single layer Ti films with a thickness of 10 nm and 100 nm deposited onto glass substrates. Both films are characterized by the only clear peak with 2θ position near 38.5°. For Ti (100 nm) film there is also another very weak peak at $2\theta \approx 35°$. It means that the Ti layers are strongly textured. Thereby analysis of the standard XRD patterns did not allow determining unambiguously the crystal structure type of the Ti films. In order to evaluate more precisely the real crystal structure of the Ti films with different thicknesses, detailed XRD analysis was carried out by changing the Psi angle from 0° to 75° (with an oscillation mode for the Phi angle) for Ti (10 nm) and Ti (100 nm) films. Fig. 3 shows different diffraction maxima measured in the above mentioned conditions. Experimentally observed and theoretical reflections data are summarized in Table 1.

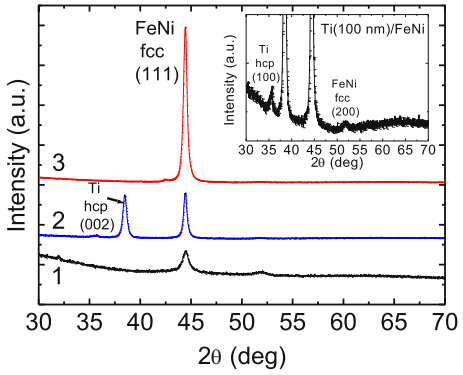

Fig. 1. X-ray diffraction spectra for FeNi(100 nm) (1), Ti (100 nm)/FeNi (100 nm) (2) and Ti (10 nm)/FeNi (100 nm) (3) films. Inset shows X-ray diffraction pattern for Ti (100 nm)/FeNi (100 nm) film at lower scale.

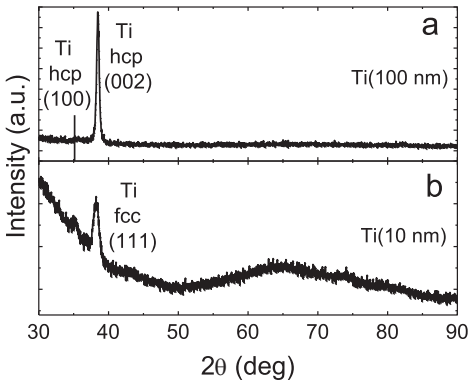

Fig. 2. X-ray diffraction spectra for Ti (100 nm) (a) and Ti (10 nm) (b) films.

Thus, we can conclude that in our case in the early stages of growth the Ti film has a cubic structure (fcc with less amount of bcc). As the thickness of the Ti film increases its structure is transformed into a hexagonal one. In some cases such a transformation was observed for Ti films epitaxially grown on single crystal substrates, for the film thickness was between several nm and tens of nm. If transformation appeared, the critical thickness value strongly depended on preparation conditions and kinds of substrates [9,10]. Moreover, FeNi layer deposited on top of Ti seed layer can not only stabilize the initial fcc stacking of titanium but can also induce a switch from an existing hcp stacking of a thicker titanium film back to fcc structure [11].

Thus, in our case, the main reason for the improved crystallinity and enhancement of the texture degree of the FeNi film using a Ti underlayer is likely an fcc structure of the thin Ti seed layer, as opposed to a decrease in the surface and elastic strain energy of the FeNi film deposited on the Ti seed layer.

The soft magnetic properties have been observed via in-plane MOKE hysteresis loops (Fig. 4). It was found that an uniaxial magnetic anisotropy was induced due to film deposition under an applied magnetic field in all studied samples. The Ti (10 nm)/FeNi (100 nm) bilayer has a minimal coercivity of 1.1 Oe and the Ti (100 nm)/FeNi (100 nm) sample has a maximum coercivity of 2.9 Oe. It is anticipated that magnetic softness of FeNi films can be optimized by controlling the Ti seed layer thickness. The difference in the coercivity is suspected to be mainly due to the interactions of the domain walls with chaotically oriented crystallites [12]. The high texturing degree of the FeNi film, deposited onto a thin layer of Ti, leads to a decrease in coercivity which is important in many technological applications like inductors, magnetoresistance or magnetoimpedance sensors [13]. Magnetic inductors and magnetoimpedance sensors with thin film-based sensitive elements require the order of the micron thickness of the FeNi film for obtaining desired properties. One of the problems to achieve a magnetic softness at a high thickness is a well-known transition in thick permalloy films into a “transcritical” state with appearance of out of plane magnetization component, high