Fabrication and magnetic properties of Co based thin films synthesized by physical vapor deposition under vacuum

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Abstract. We used thermal heating process, under a pressure of $10^{-7}$ mbar, to fabricate thin films of cobalt on monocrystalline silicon Si (100) substrates. The incident beam strikes the substrates under normal and oblique incidences within a home-made evaporation chamber. The thickness of the deposited films ranges from 18 to 400 nm. Microscopic characterizations of the films are performed with X-ray diffraction (XRD) measurements and infer that all the samples are polycrystalline, with an hexagonal close packed (h.c.p.) structure and exhibit a <0001> preferred orientation, for the perpendicularly evaporated films. The grain size is found to increase with the thickness of the magnetic layer. The values of the computed parameters allow concluding to a compressive stress for the thinnest films. The static magnetic properties have been performed by means of magnetic force microscopy (M.F.M.) and Alternating Gradient Field Magnetometer (A.G.F.M.) tools. The dynamic magnetic properties have been investigated using Brillouin Light Scattering (B.L.S.) measurements. The M.F.M. observations were performed after in-plane ac demagnetization, and stripe patterns are only observed for the thickest films, showing the weaker perpendicular anisotropies. We used the experimental results provided by these tools to compute the effective magnetic anisotropy factors $K_u$. Values of $K_u$ anisotropy constants, higher than $13 \times 10^6$ erg.cm$^{-3}$, have been found.

Keywords: X-ray diffraction, Thin films, Hysteresis, Magnetic anisotropy, Brillouin Light Scattering (B.L.S.).

1. Introduction
Ferromagnetic thin films have been intensively studied in the last two decades due to the development of new and sophisticated elaboration methods and techniques of analysis, particularly Co and alloys such as CoCr and CoPt etc [1-5]. Some materials present a desirable perpendicular magnetic anisotropy and can then be good candidates for high density storage media; their magnetic properties depend greatly on the methods and conditions of preparation and they are affected by the structural properties. In this work we report structural, static and dynamic magnetic studies of perpendicularly and obliquely evaporated Co/Si (100) thin films as a function of Co thickness. To characterize these films, a lot of techniques were performed: X-ray diffraction, Alternating Gradient Field Magnetometer (AGFM), Brillouin Light Scattering (BLS), Magnetic Force Microscopy (MFM).

2. Experimental procedures
We have evaporated, using thermal heating process under vacuum, two series of Co thin films onto monocrystalline Si (100), perpendicularly and obliquely to the targets. The 99.99 % purified cobalt
powder was placed in a crucible made of tungsten coated with alumina. Before deposition, the pressure in the evaporation chamber was around $10^{-7}$ mbar; during the evaporation the base pressure was lower than $2 \times 10^{-6}$ mbar. Each series is composed of several samples with thickness ranging from 18 to 400 nm. X-ray diffraction measurements were performed using a Siemens D-500 diffractometer with $\lambda = 1.789$ Å. The hysteresis loops of these Co films were carried out by AGFM measurements, with the external magnetic field $H$ applied perpendicular (polar configuration) and in the film plane (longitudinal configuration), and the zero-field magnetic structure has been investigated by Magnetic Force Microscopy (MFM), using a Veeco 3100 apparatus. Finally, the magnetic anisotropy in Co/Si samples was investigated by means of Brillouin Light Scattering (BLS) experiments, using a (2 × 3)–pass tandem Fabry-Perot interferometer. The thin films were illuminated by a single-mode Ar+ ion laser at the wavelength of $\lambda = 5145$ Å, with an incident power of 100 mW. The value of the transferred in-plane wave vector $q_\parallel$ is connected to $\theta$ by the relation $q_\parallel = (4\pi/\lambda) \sin \theta$. The experiments were done with different values of the intensity of the applied magnetic field, in the 0–5 kOe range.

3. Results and discussion

3.1. Structural study

The XRD spectra recorded for perpendicularly evaporated Co/Si samples exhibit 3 Bragg peaks, <10-10>, <0002> and <10-11> of hexagonal close packed (h.c.p.) Co, the most intense one being <0002> peak. All the samples are polycrystalline, with a h.c.p. structure and exhibit <0001> preferred orientation. Using the diffraction spectra we computed the values of the lattice constants $a$ and $c$. These values are 2.49 Å and 4.69 Å, respectively. The bulk parameters being $a = 2.51$ Å and $c = 4.07$ Å, our Co films are therefore under a tensile stress due probably to the growth mode of the films, a Stranski-Krastanov growing mode.

3.2. Static magnetic study

3.2.1. Hysteresis curves.

Figure 1 displays examples of hysteresis curves obtained for the longitudinal configuration (H parallel to the film plane) and the polar configuration (H perpendicular to the film plane). In the longitudinal configuration, it is easy to saturate the films, whereas for the perpendicular configuration, we have to apply a very high magnetic field to come within reach of saturation and this is typical to in plane magnetic anisotropy. From the shape of the curves we infer that the easy magnetization axis lies in the film plane, for all samples.

![Figure 1](image)

**Figure 1.** Examples of hysteresis curves obtained for the longitudinal configuration (H parallel to the film plane) and the polar configuration (H perpendicular to the film plane).
3.2.2. MFM observations.
With the aim to examine the domain configurations of our evaporated Co thin films, we used the magnetic force microscope to observe the images. Figure 2 is an image of the surface topography (a) and stripes domains (b) recorded for the thicker sample, Co (400 nm) thin film. The films present very smooth surface topography, the rms roughness being equal to a few ångströms. Obtained with a lift scan of 50 nm, the MFM image (b) shows clearly the presence of magnetic domains; the half period of these weak stripe patterns is equal to 200 nm. These weak stripes patterns are evidence of the existence of an out-of-plane component of the magnetization vector M in the thickest samples in which the magnetocrystalline anisotropy is dominant. The light and dark areas correspond to the site of up and down domains.

![MFM observations](image)

Figure 2. AFM (a) and MFM (b) images of Co (400 nm) thin film. Scan area is 20 × 20 μm.

3.3 Dynamic magnetic study
3.3.1. Brillouin light scattering.
In the most recent decades, Brillouin Light Scattering technique has been used to explore magnetic materials properties [6–9] and precisely the magnetic anisotropy.

BLS experiments were performed on our thin films under the conditions described in Section 2. In Figure 3, we show specimens of experimental and calculated Brillouin spectra obtained with $H = 5 \text{kOe}$ for Co (195 nm)/Si sample. As can be seen on Figure 3, the agreement between the experimental and the calculated spectra is good enough. It was obtained by fitting the magneto-crystalline anisotropy field $H_a$ (assumed to be uniaxial, $H_a = 2K_u/M_s$, with $K_u$ the uniaxial anisotropy constant).

In Figure 4, we display typical frequency shift as a function of applied magnetic field $H$ curves for two representative samples Co (195 nm)/Si and Co (50 nm)/Si films. The experimental data for the Damon-Eshbach (DE) are the points and the simulated predictions are the solid lines; here too, the fit is very satisfactory.

In Table 1, we present the computed magnetic anisotropy factors as a function of the thickness $t$ of the magnetic layer, for the Co/Si thin films, evaporated either perpendicular to the substrate or with an oblique incidence angle.
As can be seen in Table 1, $K_u$ decreases drastically, from 8.8 to $3.1 \times 10^6$ erg.cm$^{-3}$ for the films perpendicularly evaporated, and decreases rapidly too, from 13.7 to $7.9 \times 10^6$ erg.cm$^{-3}$ for the films obliquely evaporated, as the thickness of the magnetic layer increases from 18 to 400 nm.

A number of phenomena are at the origin of the magnetic anisotropy in thin films, namely the magnetocrystalline structure and the two-dimensional shape of the material. In the Co (18 nm) thin film, the demagnetizing field is important, which makes the shape anisotropy preponderant, and consequently, gives rise to a high value of $K_u$. In the Co (400 nm) thin film, the demagnetizing field is lower which makes the shape anisotropy lesser and infera relatively low value of $K_u$, due principally to the magnetocrystalline anisotropy.

4. Conclusion

With a homemade evaporation chamber we synthesized series of Co thin films, deposited either perpendicularly or with an oblique incidence angle with regards to the Si (100) substrate. The hysteresis curves display loops inferring that the easy magnetic axis is lying in the plane of the film. Well-defined stripes patterns are observed in the thicker films. From the Brillouin Light Scattering study we computed

| $t$(nm) | 18 | 50 | 195 | 280 | 400 |
|---------|----|----|-----|-----|-----|
| oblique | 13.7 | 12.6 | 8.4 | 8.1 | 7.9 |
| perpendicular | 8.8 | 7.6 | 5.2 | 4.3 | 3.1 |

Table 1. Anisotropy field versus thickness, for perpendicularly and obliquely evaporated films.
the magnetic anisotropy factors and found values as high as $13 \times 10^6$ erg.cm$^{-3}$ for the obliquely evaporated films, much greater than those found for perpendicularly evaporated samples.

5. References

[1] Nozawa N, Saito S, Hinata S and Takahashi M 2013 Large uniaxial magnetocrystalline anisotropy for Co50Pt50 disordered alloy films with hexagonal-close-packed stacking structure by substituting Pt with Rh J. Phys. D: Appl. Phys. 46(17) 172001

[2] Melloul A and Kharmouche A 2019 Synthesis, structure and magnetic properties of Co$_x$Fe$_{100-x}$ thin films thermally evaporated onto Si (111) substrate J. Mater. Sci: Mater. Electron. 30 13144-13150

[3] Hu H, Chen H, Yu S, Chen L, Chen J and Wu G 2006 Fabrication and magnetic properties of Co$_x$Pd$_{1-x}$ composite nanowire J. Magn. Magn. Mater. 299 170–175

[4] Kharmouche A, Cherif S, Bourzami A, Layadi A and Schmerber G 2004 Structural and magnetic properties of evaporated Co/Si(100) and Co/glass thin films J. Phys. D: Appl. Phys. 37 2583

[5] Kharmouche A 2013 Magnetic anisotropy factors of vapor deposited CoCr thin films on Si and glass substrates J. Magn. Magn. Mater. 327 91–94

[6] Hillebrands B, Mathieu C, Bauer M, Demokritov S, Bartenlian B, Chappert C, Decanini D, Rousseaux F and Carcenac F 1997 Brillouin light scattering investigations of structured permalloy films J. Appl. Phys. 81 4993

[7] Büttner O, Bauer M, Demokritov S, Hillebrands B, Kivshar Y S, Grimalsky V, Rapoport Y and Slavin A N 2000 Linear and nonlinear diffraction of dipolar spin waves in yttrium iron garnet films observed by space- and time-resolved Brillouin light scattering Phys. Rev. B 61 11576

[8] Serga A, Schneider T, Hillebrands B, Demokritov S and Kostylev M 2006 Phase-sensitive Brillouin light scattering spectroscopy from spin wave packets Appl. Phys. Lett. 89 063506.

[9] Sebastian T, Schultheiss K, Obry B, Hillebrands B and Schultheiss H 2015 Micro-focused Brillouin light scattering: imaging spin waves at the nanoscale Front. Phys. 3 35

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