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Magnetic Responses of Ultra-thin Film of Cobalt (0.7 nm) at Low Temperatures

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Abstract We studied magnetic responses at low temperatures of Au/Co ($t_{Co} = 0.7\ nm$)/Au deposited on SiO_2. By using Polar Magneto-Optical Kerr Effect (PMOKE) magnetometry, we determined the magnetization easy axis at 300 K. We used Superconducting QUantum Interference Device (SQUID) magnetometer, in polar configuration, to study the quasi-static parameters between $4-200\ K$. Our results showed that the easy magnetization axis changes direction according to the temperature.

Keywords: *SQUID, low temperature, coercivity, easy magnetization axis*

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1. Introduction

Research on magnetic materials evolved in a spectacular way during the two last decades this tendency was reinforced with the miniaturization of the devices using magnetic materials. This research is directed either towards the comprehension of very fundamental mechanisms or towards an important prospects for applications such as ultra-high density storage [1,2] or magnetic refrigeration [3-9].

To understand the fundamental mechanisms of ferromagnetic materials, for example, the cobalt ultra-thin films are good candidates. In these materials magnetization reversal plays a very important part in the technological applications. The intrinsic parameters such as coercivity, the anisotropy and the spontaneous magnetization have an undeniable effect on the magnetization reversal. Several studies are devoted to the comprehension and the control of the behaviour of these parameters to the room temperature [10-29] but very little are devoted to the comprehension of the behaviour of these parameters to low temperatures [30].

The aim of this paper is to study the evolution of coercivity, spontaneous magnetization and the anisotropy, of cobalt ultra-thin film, at low temperatures.

2. Material and Methods

2.1. Sample and Structural Characterizations

Si (100) substrate is beforehand cleaned by ultrasounds in an acetone bath. After the cleaning, this substrates is thermally oxidized in a furnace at 1200°C during 2 hours. This time is sufficient for the formation of an oxide layer on the silicon surface substrate.

Au/Co/Au film were prepared by electron beam evaporation in an ultrahigh vacuum chamber, with a base pressure of about 10^{-9} *Torr* and approximately 10^{-8} *Torr* during deposition on SiO_2, at room temperature.

A first 25 nm thick Au film is deposited on the substrate at a deposition rate of 2.5 nm/min, as calibrated with a quartz microbalance, followed by annealing at $423\ K$ during $1\ h$ to reduce the surface roughness.

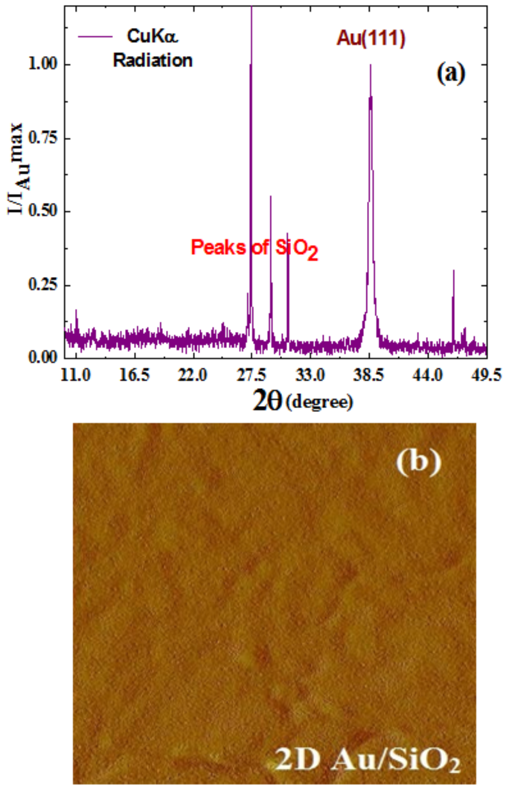

Figure 1. (a): XRD spectra of a 25 nm thick Au layers deposited on SiO_2 substrate. (b): 2D AFM image of a 25 nm thick Au buffer layer deposited on SiO_2 substrate

The Au film is (111) textured, as shown by X-ray diffraction (Figure 1(a)). Figure 1(b) shows the 2D AFM image of the Au buffer layer after annealing. The surface roughness (root mean square: rms) was measured to be about 0.2 nm. Using the surface corrugation obtained from 2D AFM, we estimate a lateral grain size of 40–60 nm.

Cobalt layer with thicknesses (t_{Co}) equal to 0.7 nm is then deposited on the Au/SiO_2 at a deposition rate of 0.2 nm/min. Finally, a second Au layer with a thickness about of 5 nm is deposited on top of the cobalt layer.

The (111) texture of the Au buffer layer suggests a possible epitaxial growth of the cobalt layer with the Hexagonal Close-Packed (0001) structure [31,32,33].

2.2. Magnetic investigations

Magnetic hysteresis loop, at a field sweep rate of $d\mu_0 H/dt = 1.2\, mT$, were recorded at room temperature (RT) by polar magneto-optical Kerr effect magnetometry (PMOKE) using a He–Ne laser ($\lambda = 633\, nm$). Figure 2 shows PMOKE hysteresis loop for this sample. The full remanence (M_r/M_s) = 1 indicates that its magnetic anisotropy of this sample is perpendicular to the magnetic layer.

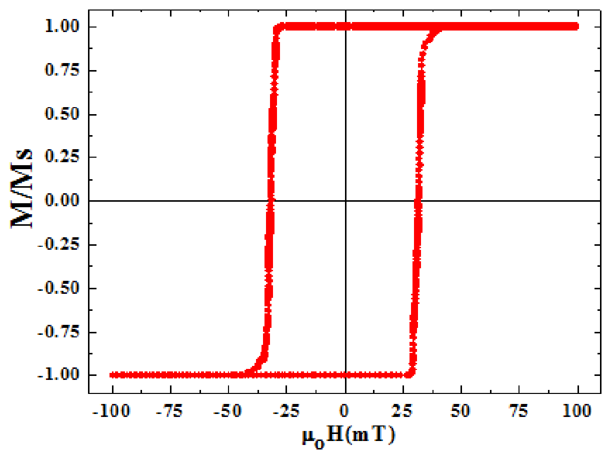

Figure 2. Quasistatic hysteresis loops of Au/Co(0.7 nm)Au/SiO_2 measured at 300 K by PMOKE.

The anisotropy of this sample was determined by PMOKE with a method described in our previous works [19,21].

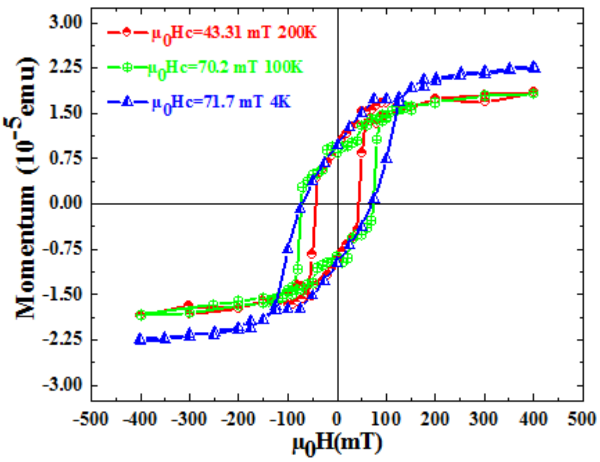

Figure 3. Hysteresis loops of Au/Co(0.7nm)/Au recorded at 200, 100 and 4 K, in polar configuration

We used Superconducting QUantum Interference Device (SQUID) magnetometer, in polar configuration, to study the quasi-static parameters of this magnetic layer at low temperatures. On the Figure 3 are presented magnetic responses of this sample at low temperatures.

In Table 1 below are summarized data deduced from quasi-static characterizations.

Table 1.

Temperature (K)	4	100	200	300
$\mu_0 H_C (mT)$	71.7	70.2	43.31	31.6
$M_S (10^6\ A/m)$	1.61	1.32	1.32	1.23
$K_{1eff}\,(10^5\, J\cdot m^{-3})$	-	-	-	2.4

3. Results and Discussion

3.1. Coercivity Depending on Temperature

The hysteresis loops presented on Figure 2 and Figure 3 show that the coercive field depends on the temperature. $\mu_0 H_c$ vs T is plotted on Figure 4. On this Figure 4, one can see that between $4 - 100\ K$, which we call zone (I), the coercive field vary very slightly according to the temperature but beyond 100 K, in zone (II), $\mu_0 H_c$ decrease quickly according to the temperature. This kind of behaviour at low temperatures is observed on other Au/Co/Au systems where the thicknesses of cobalt t_{Co} are higher than 1 nm [30].

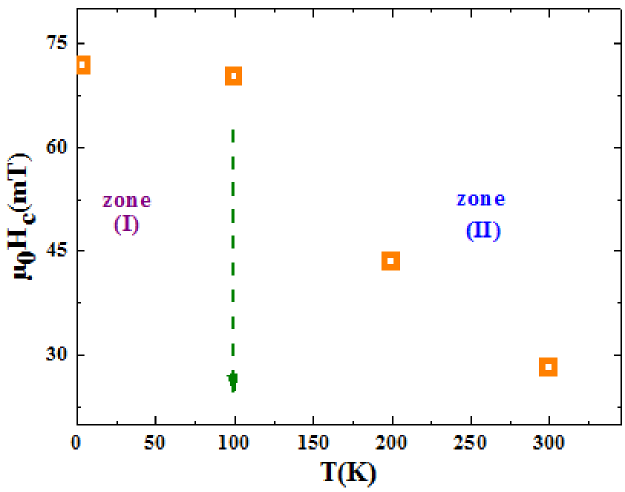

Figure 4. Coercive field depending on the temperature of Au/Co(0.7nm)/Au

Indeed the temperature dependence of the coercivity can be expressed as [4]:

$$\mu_0 H_c = a\frac{(\Delta\gamma)^2}{\gamma_0} - b\frac{k_B T}{t_{Co}}, \quad (1)$$

where $\Delta\gamma$ is local fluctuations of the wall energy, γ_0 is the wall energy, with $a, b > 0$.

By using the concept of dimensional analysis we can put the equation (1) in this form:

$$\mu_0 H_c = \mu_0 H_0 - b\frac{k_B T}{t_{Co}}, \quad (2)$$

$\mu_0 H_0$ is the coercive field at $0\ K$. In zone (I) equation (1) is applicable because this zone is between $0 - 100\ K$. In the zone (II) the equation is reduced to:

$$\mu_0 H_c = -b_2 \frac{k_B T}{t_{Co}}. \quad (3)$$

With $b_2 > 0$.

We used the equations (2) and (3), respectively for the zones (I) and (II) to deduce $\mu_0 H_0$, b and b_2. These adjustments are presented on Figure 5.

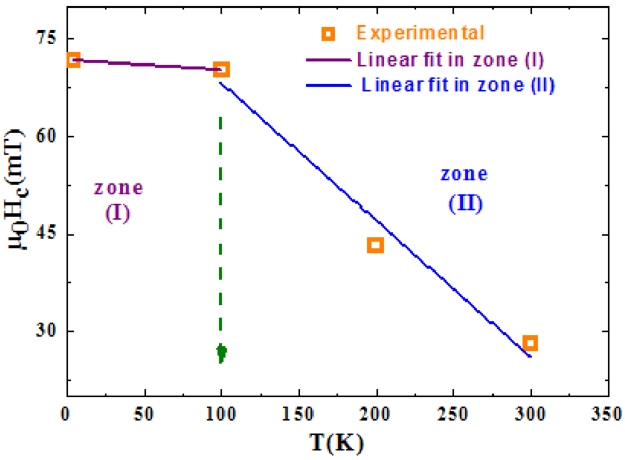

Figure 5. Fitting of coercive field depending on the temperature of Au/Co(0.7nm)/Au

From the fittings we found in the zone (I) $\mu_0 H_0 = 71.76\ mT$, $b = 79.23 \times 10^{10}\ A^{-1} m^{-1}$ and in the zone (2) $b_2 = 1070.29 \times 10^{10}\ A^{-1} m^{-1}$. The value of $\mu_0 H_0$ found at $0\ K$ is practically the same as that found for $\mu_0 H_C$ at $4\ K$. This result confirms the fact that below $4\ K$ the effects of the temperature are almost null. The decrease of the coercivity with the temperature shows that the process the magnetization reversal is thermally activated in this sample. For parameter b one can see that it increases with the temperature.

3.1. Anisotropy and Easy Magnetization Axis

The magnetization of crystallized matter is directed preferentially according to certain crystallographic directions. This is call magnetic anisotropy which is explained by the symmetry of local environment of the magnetic atoms. In the case of Hexagonal Close-Packed (HCP) system the anisotropy is along only one axis and one speaks about uniaxial anisotropy. In the case of Face Centered Cubic structure (FCC) there may be several easy magnetization axis. If one record a hysteresis loop along the easy magnetization axis one has a square loop [34].

Our hysteresis loops presented on Figure 2 and Figure 3 were all carried out in polar configuration. The loop, recorded at 300 K, presented on Figure 2 is square. The squareness of the loop shows that the easy magnetization axis is perpendicular to the magnetic layer at 300 K. The loops presented in Figure 3 are realized by SQUID at 200, 100 and 4 K. In the three cases of temperature the loop is not square but present rounded corner. The rounding of the loop is accentuated with the temperature lowering. Indeed the loop carried out at 200 K presents an abrupt transition from the up to down state whereas at 4 K this abrupt transition disappeared. The change of the shape of the loop could be related to the change of the easy magnetization axis. Since the easy magnetization axis orientation is related to the structure of the magnetic layer [34] we deduce thus that the change of the loop shape would be due to a probable phase change during the temperature lowering.

With regard to magnetization we notice that the greatest value is found at 4 K, what confirms the fact that the effects of the temperature are almost null around 4 K.

4. Conclusion

The study of magnetic responses of ultra-thin film of cobalt (0.7 nm) at low temperatures. The evolution of coercivity according to the temperature revealed below 100 K the thermal effects are weak and from 4 K and below these effects are negligible. The hysteresis loop shape according to the temperature let's think that the temperature lowering induce a change phase of the crystalline structure. Thus, we show that the anisotropy change according to the temperature.

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