Journal Homepage: -www.journalijar.com
INTERNATIONAL JOURNAL OF ADVANCED RESEARCH (IJAR)
Article DOI:10.21474/IJAR01/7537
DOI URL: http://dx.doi.org/10.21474/IJAR01/7537
ISSN NO. 2320-5407

RESEARCH ARTICLE

THE THERMAL OXIDATION EFFECT OF THE SINGLE CRYSTAL SILICON (100) ON THE MAGNETIC PROPERTIES OF ULTRA-THIN FILMS OF COBALT.

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Manuscript Info

Manuscript History

Received: 11 June 2018
Final Accepted: 13 July 2018
Published: August 2018

Keywords:-
AFM, thermal oxidation, coercivity, first order of the anisotropy constant.

Abstract

We studied the systems Au/Co ($t_{Co} = 0.7, 0.8, and 1\ nm$)/Au deposited on Si and SiO_2 by polar magneto-optical Kerr effect magnetometry (PMOKE). Topologies of Si and SiO_2 were studied by atomic force microscopy (AFM). We showed that the oxidation of Si induced a change in the evolution of the coercive field and that of the first order of the anisotropy constant according to the thickness of cobalt.

Introduction:-

In ultra-thin films, layers' morphology plays an important role on many physical properties such ascoercivity, magnetic anisotropy, nucleation field and the magnetization reversal dynamics which continues to present a great interest in magnetism as well as in spintronic device applications. The considerable efforts of research devoted to the comprehension of the mechanisms which influence the magnetic properties are due to the development of the techniques such as magneto-optics, microscopy Kerr, the atomic force microscopy (AFM) and others. Several works showed that magnetic parameters such as the coercive field, the magnetic anisotropy constant, the saturation magnetization depends on the magnetic layer thickness [1-4]. Our former work showed the effect of the morphology of the magnetic layer on the magnetic properties more precisely on the dynamics of inversion of magnetization [4,5]. In this paper we show that the morphology of the magnetic layer can act on the magnetic parameters such as the coercive field, the magnetic anisotropy even if one keeps the thickness of the magnetic layer constant.

Material and methods:-

2.1 Substrate of Si(100) and its oxidation

Si(100) substrate is beforehand cleaned by ultrasounds in an acetone bath. The thermal oxidation of the substrate of silicon is done by putting it in a furnace at $1200\ °C$ during 2 hours. This time is sufficient for the formation of an oxide coating on the silicon surface substrate. The Surfaces of the two substrates were explored byAtomic Force Microscopy (AFM). The probe tip radius is smaller than $5\ nm$. On the figure 1 are presented the 2D and 3D AFM images of the silicon substrate before and after its oxidation.

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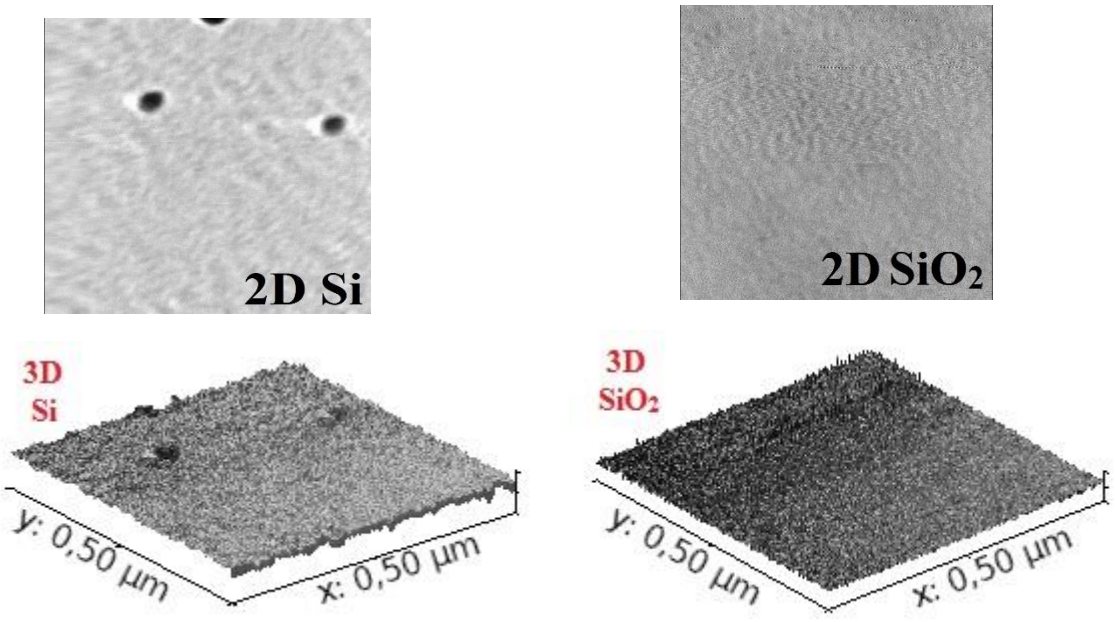

Fig. 1:-2D and 3D AFM images of Si and SiO_2substrates.Image area: $0.5 \times 0.5\ \mu m^2$.

The images obtained by Atomic Force Microscopy were analyzed by Gwyddion software. In order to be able to evaluate the effect of thermal oxidation on the silicon substrate we made morphological analyze of the two surfaces. The morphological analysis allowed us to find a roughness rms (root mean square) about of $1.39\ nm$ for the Si substrate and that of $1.08\ nm$ for the SiO_2 substrate. Thus, lowest roughness is found on SiO_2 substrate. In order to have more detailed idea on two surfaces we also made statistical analyzes. On the figure 2 are presented slopes on the two substrates along a given direction.

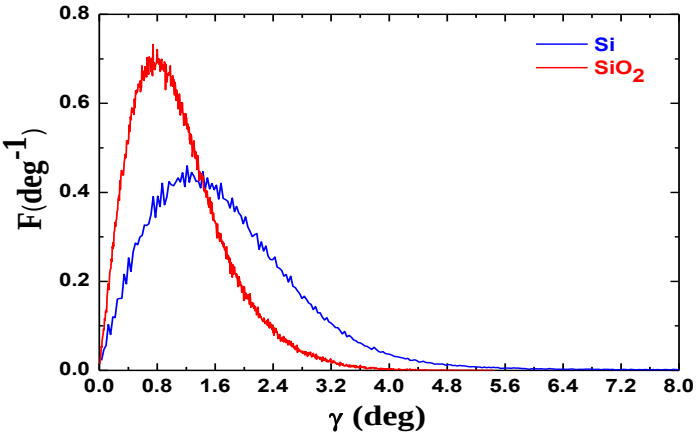

Fig. 2:-Slope distribution according to substrate, determined from 2D AFM images in each case.

The average of the slopes is about of $1.26°$ for Si and about of $0.74°$ for SiO_2, what is an agreement with the diminution of roughness observed after the thermal oxidation of Si. From 2D AFM images of figure 1 we counted the number of peaks along a certain direction chosen on each image. On the figure 3 are presented the curves of the number of peaks according to altitude $Z\ (nm)$ along a direction given on each image 2D AFM of figure 1.

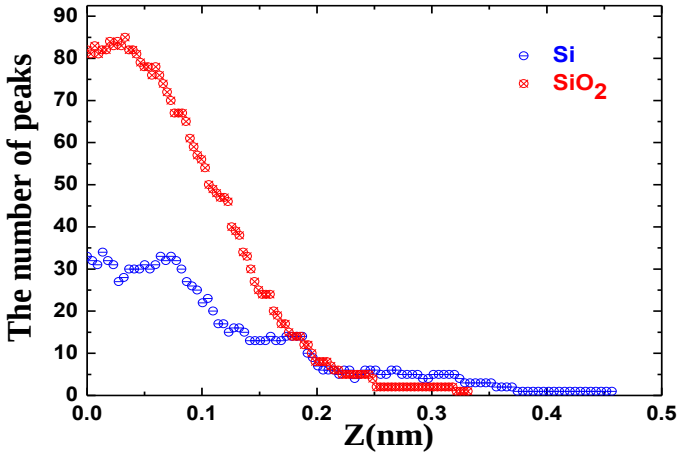

Fig.3:-The curves of the number of peaks according to the altitude Z (nm) on Si and SiO_2 substrates.

In both cases the peaks don't reach $0.5\ nm$, which confirms the magnitude order of the roughness rms found for these two substrates. On silicon thermally oxidized the great number of peaks have a height Z around $0.1\ nm$ and the maximum height is slightly higher than $0.3\ nm$ whereas on natural silicon certain peaks are around $0.45\ nm$ height. This result shows that thermal oxidation improves topology of the silicon substrate [5].

2.2 Sample and structural characterizations

Au/Co/Au films were prepared by electron beam evaporation in an ultrahigh vacuum chamber, with a base pressure about of $10^{-9}\ Torr$ and approximately $10^{-8}\ Torr$ during deposition. All deposition processes were performed at room temperature (RT).

A first $25\ nm$ thick Au film is deposited on the substrates of Si and SiO_2 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. These layers were studied by X-ray diffraction (XRD) and by AFM. The Au buffer layer is in each case (111) textured, as shown by XRD spectra (Fig. 4)

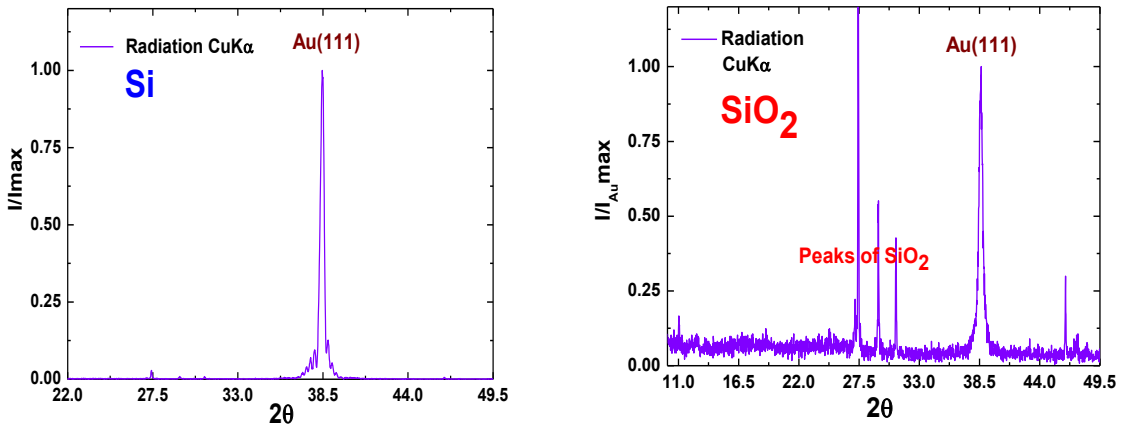

Fig. 4:-Spectra of XRD,$\theta - 2\theta$, of the Au buffer layer deposited on Siand SiO_2.

The spectrum of X-rays diffraction of the Au/SiO_2 system presents additional peaks apart from that of Au(111). These peaks, obviously, would due to the recrystallization of the silicon surface. Fig. 5 shows the 2D AFM images of the Au buffer layer surface on these two substrates.

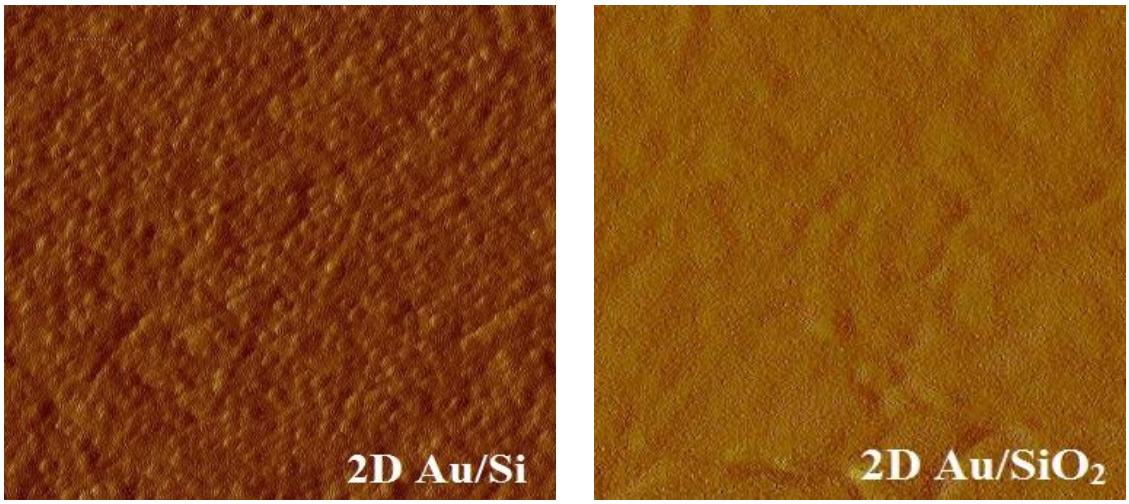

Fig. 5:-2D AFM images of the $25\ nm$ thick Au buffer layers deposited on Siand SiO_2 substrates.

We used the 2D AFM images of figure 5 to do the morphological studies of the Au buffer layers. Thus, the roughness of the Au buffer layer deposited on Si(100) is equal to $0.3\ nm$ and that the Au buffer layer deposited on the SiO_2 is $0.2\ nm$.

We measured on these two buffer layers the number of peaks along a certain direction. The number of peaks according to altitude $Z\ (nm)$ on $25\ nm$ thick Au buffer layers are represented on the fig. 6.

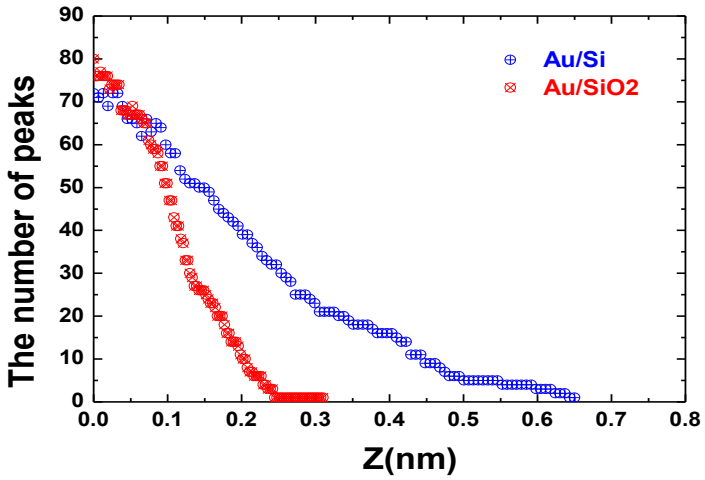

Fig. 6:-The number of peaks along a certain direction, according to altitude $Z\ (nm)$ on Au(25nm)/Si andAu(25nm)/SiO_2.

The peaks of low amplitudes are on the Au buffer layer deposited on SiO_2 and this is in agreement with lowest roughness found on this substrate. The granulometry of buffer layers was also studied by means of the AFM. We used the surface corrugation obtained from the 2D AFM images to estimate the lateral grain size in each case. For Au on Si we estimate the lateral grain size of $15 - 25\ nm$ and on SiO_2 it is about $40 - 60\ nm$.

Cobalt layers with different thicknesses (t_{Co}= 1, 0.8 and 0.7 nm) are then deposited on the Au/Si and 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 layer suggests a possible epitaxial growth of the cobalt layers with the hcp (0001) structure [6–8].

Results and discussion:-

Magnetic hysteresis loops, at a field sweep rate of $d\mu_0 H/dt = 1.2\ mT/s$, were recorded at room temperature (RT) by polar magneto-optical Kerr effect magnetometry (PMOKE) using a He–Ne laser ($\lambda = 633\ nm$). Fig. 7 shows PMOKE hysteresis loops for the six samples. The full remanence $(M_r/M_s = 1)$ of the six samples indicates that their anisotropy is perpendicular to the magnetic layer. For the samples realized on Si the coercivity decreases when the thickness of cobalt decreases [9], whereas the opposite behavior is observed for the deposits realized on SiO_2. The evolution of the coercivity observed on SiO_2 is in conformity with what is usually observed in Au/Co/Au systems with cobalt thicknesses in the same range as the ones studied here, where coercivity generally increases with decrease of the cobalt layer thickness [2,10]. The decrease of the coercivity observed on Si would be, at first sight, due to the small grain size $(15 - 25\ nm)$ of the Au buffer layer found on this substrate or probably due to the effect of the morphology of the Au buffer layer [4]. In fact, the detailed analyze of morphologies of the substrates and the Au buffer layers presented on fig. 2,3 and 6 showed that the values of the distributions of the slopes and the peaks are great on Si, and this would be at the origin of the decrease of the coercivity observed on Si. Thus we allot the change of the coercivity depending on the t_{Co} to the effect of the thermal oxidation.

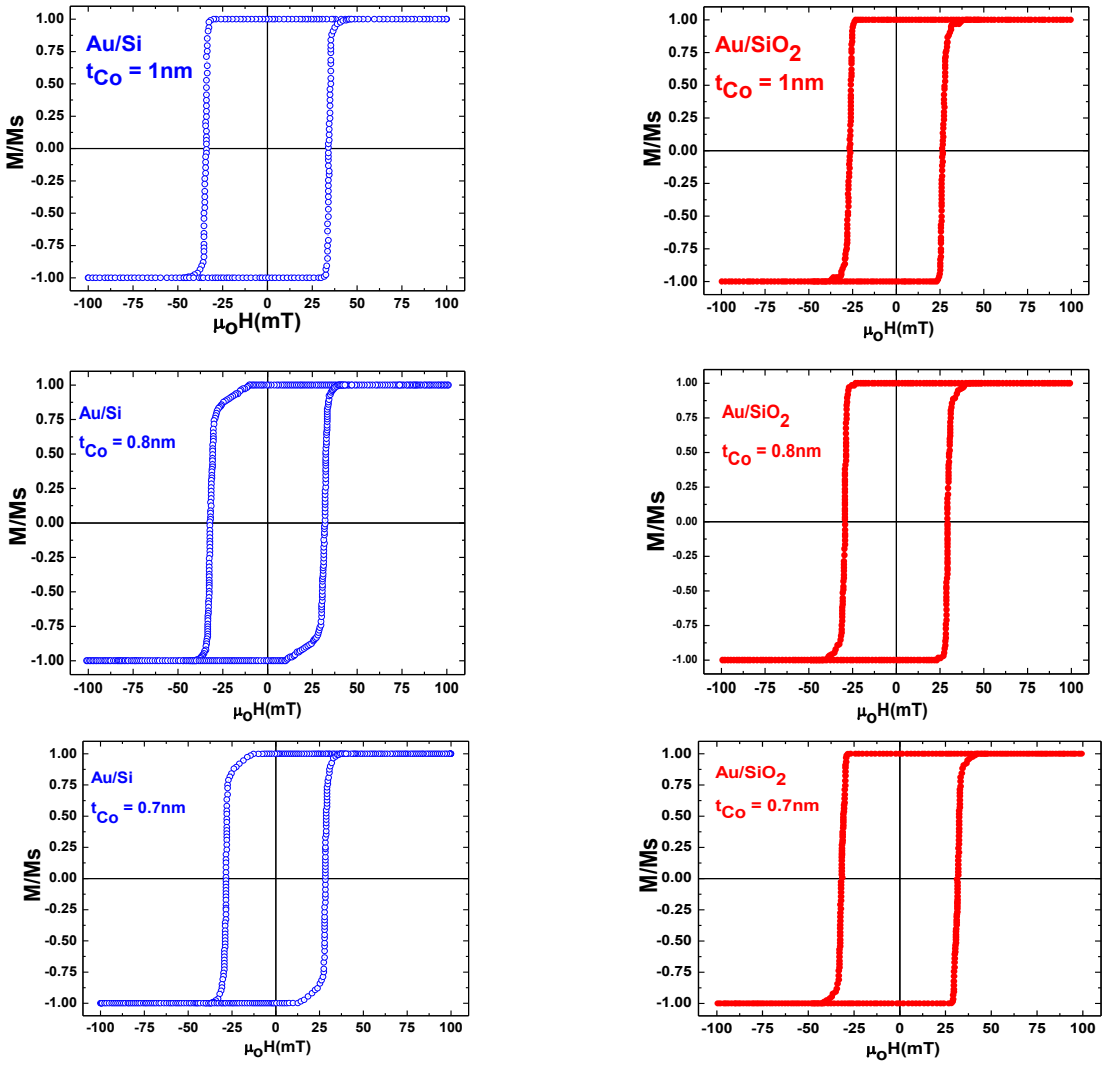

Fig. 7:-Quasistatic hysteresis loops of Co films measured at $300\ K$, of thicknesses$t_{Co} = 1\ nm, 0.8\ nm$ and $0.7\ nm$, deposited on Si and SiO_2.

The coercivity has a nucleation or wall propagation origin, but being also usually correlated with the anisotropy let us discuss of the anisotropy of our samples. The full remanence of loops confirms that cobalt grows with the compact hexagonal structure in these samples. In this case, the anisotropy is uniaxial and the anisotropy energy density can be written as:

$$E = K_{1eff}\sin^2(\theta) + K_2\sin^4(\theta), \quad (1)$$

where θ is the angle between the magnetization and the perpendicular to the plane of the film. The second-order term K_2 isassumed of magneto-crystalline origin whereas the first-order effective anisotropy constant K_{1eff} can be written as :

$$K_{1eff} = (K_V - 2\pi M_S^2) + \frac{2K_s}{t_{Co}}, \quad (2)$$

$-2\pi M_S^2$ is the dipolar term, where M_S is the spontaneous magnetization. K_V and K_s and are the volume and the interface contributions to the anisotropy. Expression (2) shows clearly that the anisotropy should increase when the cobalt thickness t_{Co} decreases, for epitaxial layers or for very small interface roughness. The PMOKE technique was also used for magnetic anisotropy measurements in our samples, at 300 K. The method consists to measure the perpendicular magnetization component when a magnetic field is applied along a direction slightly tilted with respect to the in-plane direction. Then, the anisotropy constants are determined from the fitting of the coherent rotation branch of the obtained $M-\mu_0 H$ hysteresis loop [4]. Values of coercive field $\mu_0 H_C$, K_{1eff} and K_2 are summarized in table 1.

Table 1:-Data obtained from the quasi-static characterizations.

Substrate	Si			SiO_2		
$t_{Co}(nm)$	1	0.8	0.7	1	0.8	0.7
Temperature (K)	300	300	300	300	300	300
$\mu_0 H_C(mT)$	34.00	32.10	28.30	26.50	29.20	31.60
$K_{1eff}(10^5 J\cdot m^{-3})$	2.50	1.79	1.60	2.05	2.31	2.4
$K_2(10^5 J\cdot m^{-3})$	0.28	0.29	0.31	0.53	0.54	0.52

Our coercivity values are slightly lower than the ones reported in the literature for similar systems [2,10,11]. Let us note that the coercivity with few mT only was reported [12]. The values of K_{1eff} in table 1 are almost twice smaller than the literature value [2] and we allotted this to the effect of the morphology of the Au buffer layer [4,9].

In order to perceive the effect of the thermal oxidation Si (100) we represented on the figure 8 coercivity $\mu_0 H_C$ and anisotropy K_{1eff} dependence of the cobalt thickness t_{Co}.

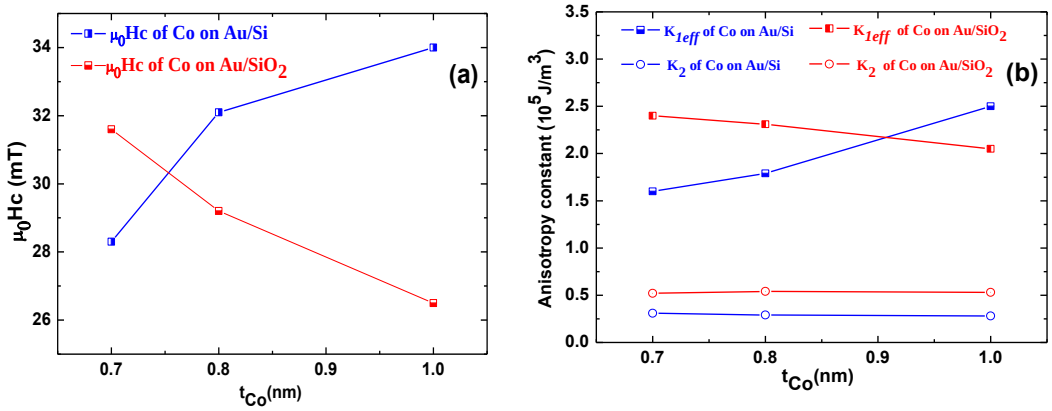

Fig. 8:- (a): Coercivity dependence of the cobalt thickness. (b): Anisotropy dependence of the cobalt thickness.

The fig. 8(b) shows clearly that K_2, in the both cases, is independent of the thickness of cobalt. K_2 is higher for the deposit carried out on SiO_2. K_2 being purely of magneto-crystalline origin, the results presented on fig. 8(b) lets think that the magneto-crystalline effects would be important in the deposits realized on SiO_2. An observation of the graphs of figure 8 shows that, on each substrate, $\mu_0 H_C$ and K_{1eff} have similar evolutions according to the cobalt thickness t_{Co}, this enables us to correlate $\mu_0 H_C$ to K_{1eff}.

Conclusion:-

We studied the systems Au/Co ($t_{Co} = 0.7, 0.8, and 1\ nm$)/Au deposited on Si and SiO_2. Surfaces of the two substrates were studied by AFM. The studies by AFM revealed that the thermal oxidation of Si improves the topology of the substrate. On the range of cobalt thickness studied, the coercivity increases with the thickness of cobalt (t_{Co}) for the deposits realized on Si whereas for the deposits realized on SiO_2 coercivity decreases with the increase of t_{Co}. On each substrate the first order of the anisotropy constant (K_{1eff}) has the same evolution as coercivity according to t_{Co}. Thus we conclude that coercivity is strongly correlated to K_{1eff}.

Acknowledgments:-

This work is the result of a collaboration between the LMOP laboratory (Tunisia) and the University of Kara, Togo. We acknowledge the help of LMOP in Tunisia and that of Néel Institute, France.

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