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EFFECTIVE ANISOTROPY OF FE/SI THIN FILMS AND ITS NANOSTRUCTURE

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Abstract The 5 to 150 nm thicknesses of Fe layers have been deposited by evaporation method onto Si substrates. Magnetic properties of samples are measured by using Magnetic Force Microscopy (MFM) and Alternating Gradient Force Magnetometry (AGFM). Structural and magnetic properties of samples have been reported from domains structure in MFM images as well as hysteresis loops in AGFM results. The domains width in Fe samples with 100 nm thickness were estimated about 2–4 μm. The XRD patterns are also show the formation of β-$FeSi_2$ phase after annealing up to 700°C. The calculated effective anisotropy for samples with different thicknesses also shows oscillations with increasing Fe layer thickness.

Keywords: magnetic properties, Fe thin films, magnetic anisotropy, MFM

1. Introduction

In recent years, research in metallic magnetic multilayers is one of the most active and exciting areas in solid state physics, since such multilayers can exhibit novel and interesting physical effects with technologically important applications like magnetic recording media, devices, sensors and spintronics [1]. One of the most interesting systems in this field finds to be Fe/Si multilayers. The structural and growth-mode correlations with magnetic properties become an ongoing challenge to materials research developments on multilayered magnetic-film structures. The effects of semiconductor substrates on physical properties of thin films have been thoroughly investigated [1–8]. On the other hand, surface roughness and thin films interfaces have strongly influences in magnetization, hysteresis loop and electrical properties [9,10]. Experiments have been demonstrated that surface induces an in-plane uniaxial magnetic anisotropy in a variety of magnetic thin films grown on semiconductor surfaces [11]. As the thickness of layers is reduced, their properties are expected to be strongly influenced by surface and interfaces, which are inevitably rough at atomic scales. Recently magnetic anisotropy, the existence of a positive (perpendicular) anisotropy, has attracted a lot of attention among the magnetic properties of Fe thin films. In this paper, magnetic properties of Fe thin layers on different Si substrates have been reported. For this purpose, we study the effect of Si(111), Si(100) substrates on the structural and magnetic properties of evaporated Fe thin films. For each experiment, different Fe thicknesses are considered.

2. Experimental technique

Fe thin films were grown on 1 cm^2 substrates by thermal evaporation method. The substrates were refreshed in diluted HF and cleaned by the standard procedures before loading into chamber. Iron ingots from a 99.99% purified Fe powder evaporated using electron gun at 0.3 nm/s and 10^{-8} torr pressure. The film thicknesses were also measured by vibrating quartz system. The Fe films were grown with different thicknesses (5–150 nm). Structural properties of samples were analyzed by X-ray Diffraction (XRD), High-Temperature XRD (HT-XRD) and Atomic Force Microscopy (AFM). Magnetic properties were measured by Magnetic Force Microscopy (MFM) and hysteresis loops were obtained by Alternative Gradient Force Microscopy (AGFM) units.

3. Theoretical framework of effective anisotropy

For anisotropy ferromagnetic films investigation, the thicknesses of films are important parameters. Film thickness should be considered in the coupling volume over which the anisotropy is averaged, since the averaging depends on the length scale perpendicular to the film plane. Therefore, we have taken the coupling volume over the anisotropy which should be averaged as $V = L_e^2 d$, where d is the film thickness. L_e is the ferromagnetic exchange length which is determined as $L_e = \left(A/K_1\right)^{1/2}$, where A is the exchange constant and K_1 is the first anisotropy constant. The number of grains (crystallites) contained in the coupling volume is $N = L_e^3 d / D^3$ where D is the average grain size. The effective anisotropy K_{eff} is given by $K_{eff} = K_1 / \sqrt{N}$. So, in the case of thin polycrystalline films the effective anisotropy is given by

$$K_{eff} = \frac{K_1^2 D^3}{Ad}. \tag{1}$$

The last expression is valid for film grain size D which is smaller than the exchange length L_e. The relation between coercivity and effective anisotropy is given by $H_C = p_c K_{eff} / M_s$, where $p_c = 0.64$ is a dimensionless pre-factor.

4. Results and discussion

a) Structural properties

XRD experiments were performed on all samples. For very thick Fe on Si(100) and Si(111) substrates, no peaks were seen in the XRD spectra. It is due to distributed randomly oriented grains, thus the peaks are too weak to be detected due to the sensitivity of the instrument and no diffraction peaks could be clearly seen in the spectra in accordance with results [3]. For Fe layer with about 50 nm thick on the two substrates, Fe grows with (110) texture and has a bcc structure. Fig.1 shows

HT-XRD patterns for Fe on Si(100) substrate. All Fe/Si(100) samples were annealed up to 600^{o}C for 120 min in the chamber with a vacuum of about 10^{-5} mbar. Fig.2 shows HT-XRD patterns of Fe/Si(100) and Fe/Si(111) samples annealed up to 1000^{o}C for three hours in the chamber with a vacuum of about 10^{-5} mbar. After annealing at 250^{o}C, the substrate surface is covered by a thin Fe-rich layer and then Si diffused into the Fe layer. After annealing at 450^{o}C, the Fe/Si atomic ratios become almost independent of the excitation energies. This indicates the chemical composition is even from the surface to the largest analysis depth. The results of valence-band spectra suggest the formation of β-$FeSi_2$, this peak is clearly seen in Fig.2. We also continue annealing up to higher temperature, after annealing at 700^{o}C, the result clearly shows the formation of thin Si layer at top most of the surface. X-ray diffraction also indicates that magnetic annealing has obvious effects on the texture of the FeSi alloy.

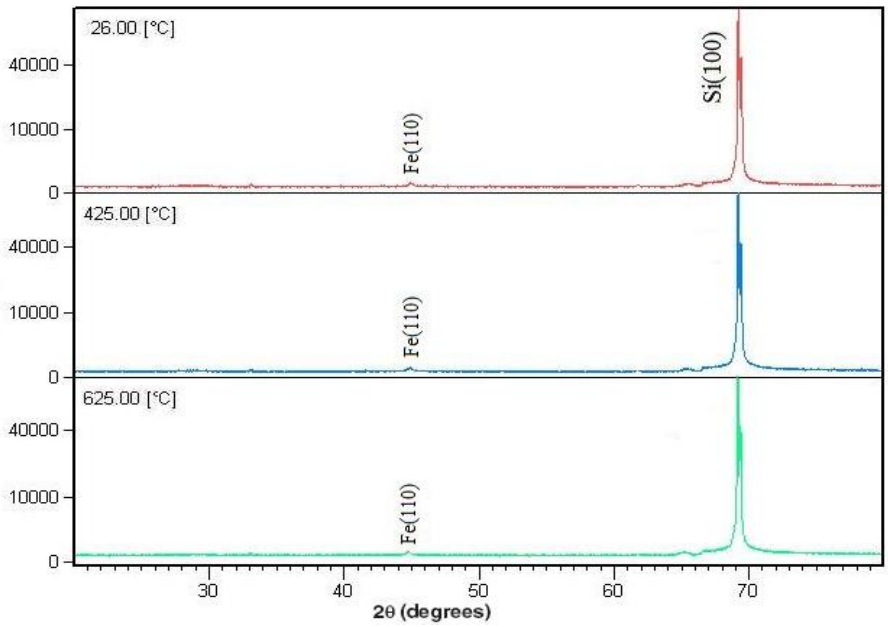

Fig.1. HT-XRD patterns for Fe film on Si(100) substrate.

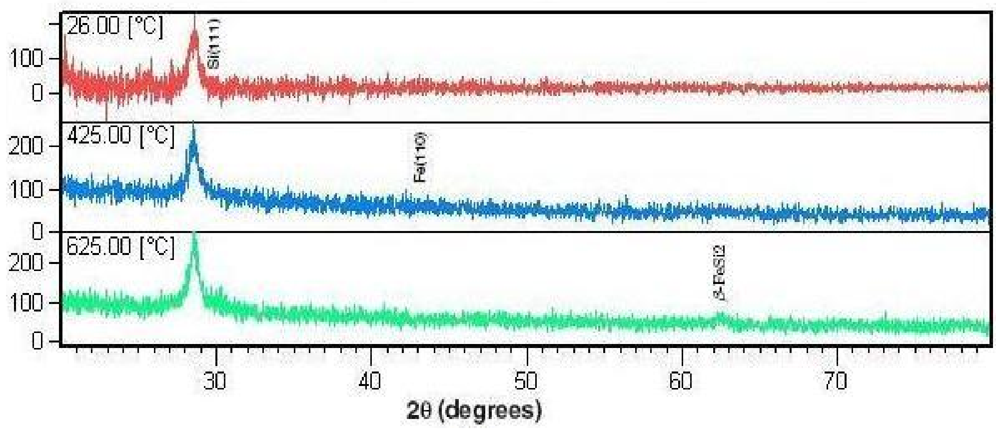

Fig.2. HT-XRD patterns for Fe film on Si(111) substrate.

AFM technique has been used to study the roughness of the surface of these Fe films. An example of AFM 3-D image is shown in Fig. 3 with four thicknesses of Fe layers. The scanned area is 5×5 μm. The root-mean-square(rms) surface roughness was estimated from the AFM image. We found that for all samples the rms values are between 0.02 and 0.06 nm. These values are typical ones for Fe as reported in several studies; e.g. for Fe thin films electrodeposited on copper substrate, the measured rms value was 2 nm. Also, Dreyer et al. reported a rms value of 0.51 nm in a 20 nm thick e-beam evaporated Fe/Si(001) [13]. Our results show that with increasing thickness of Fe layer the RMS value varies non-uniformly. In critical thickness, 35 nm of Fe coating is obviously not uniform and distributed like randomly small islands on the substrate.

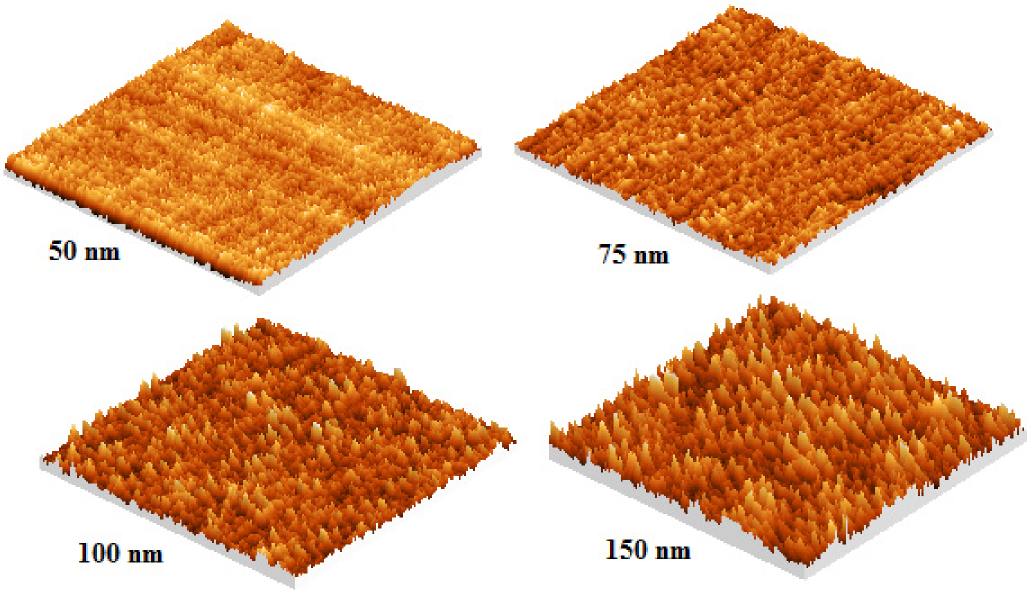

Fig.3. AFM 3-Dimensional images of 5×5 μm scan of Fe layer with different thicknesses.

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b) Magnetic properties

The MFM picture obtained at the irradiated areas show distributed magnetic domains, as depicted in Fig.4 for Fe thin films on Si (100) substrate. MFM was operated in a non-contact, dual-pass lift-mode technique with commercially available, CoCr-coated Si MFM tips. The tips were perpendicularly magnetized. The scan height was 25 nm. In this image, one can see bright and dark areas that can be regarded as corresponding to the position of inner down and up domains. The periodicity or the width of the domains depends on the irradiation dose, ranging about 2–4 μm. For better illustration, in Fig.5b and Fig. 6b, we show a zoom picture of the magnetic domain structure. Because of the small coercive field of the magnetic surface and the influence of the magnetic tip, we have observed that the magnetic domains distribution depends on the distance between tip and surface. We note that measurements on different magnetic samples indicate that distance between the tip apex and effective position of magnetic moment in tip depends on the magnetic properties of measured surface and therefore calculated magnetic moment from MFM data should be taken as a rough estimate only [14].

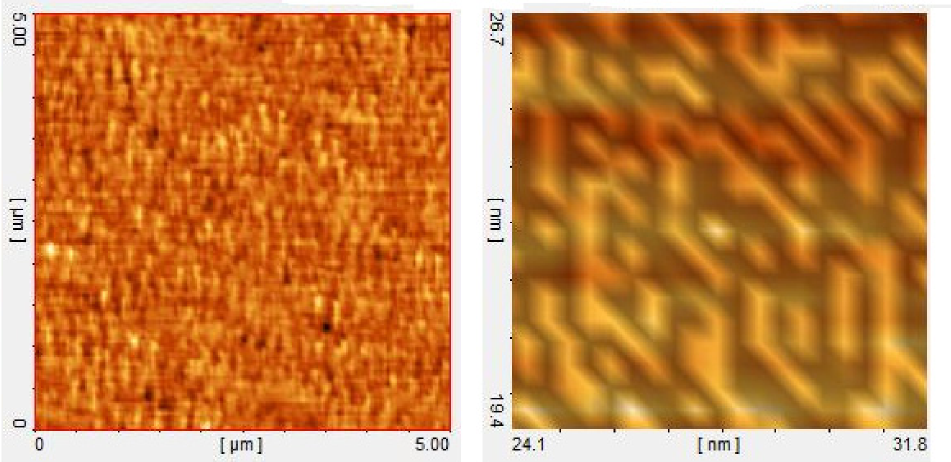

Fig.4. The AFM morphology of surface (left) and MFM magnetic domain (right) images of 100nm, Fe/Si(100) thin film.

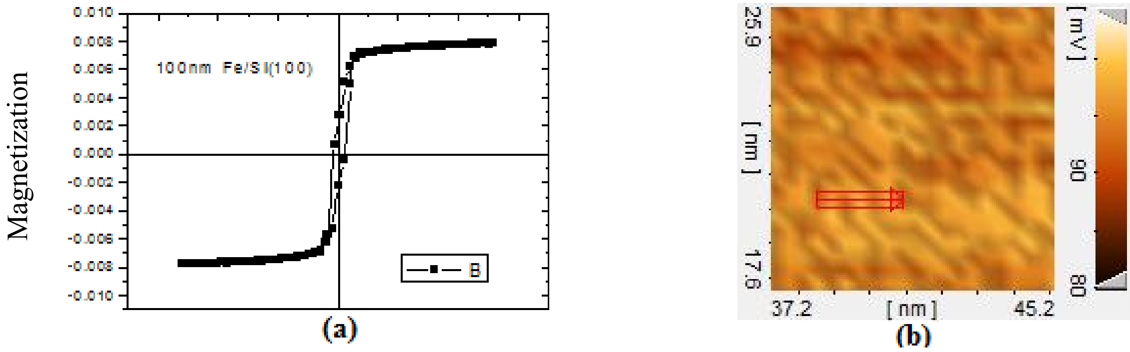

Fig.5. Magnetization and MFM surface view of as deposited Fe/Si(100).

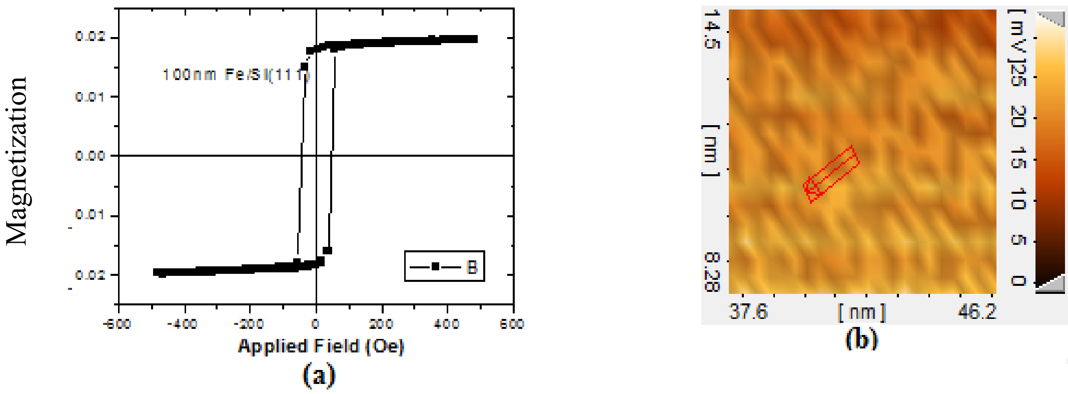

Fig.6. Magnetization and MFM surface view of as deposited Fe/Si(111).

The in-plane hysteresis loops of Fe films were measured by AGFM. The results are shown for 100 nm Fe films on Si (100) and Si (111) substrates, in Fig. 5a and 6a, respectively. The coercive field measured for the Fe films is about 100 Oe. The measured hysteresis loops show that the coercive field decreases while the saturation field increases when the external field is turned away from the direction parallel to the steps to the direction perpendicular to the steps, and such uniaxial anisotropy increases with increasing step density [12]. As the film thickness decreases, the fraction of the soft phase increases substantially. Our results show that the samples exhibit square hysteresis loops except for the film of 50 nm thickness.

c) Effective anisotropy

The K_{eff} values thus obtained are plotted in Fig.7 as a function of Fe layer nanostructure thin film. It is also shown its oscillation when thickness is increased for both Si(111) and Si(100) substrates.

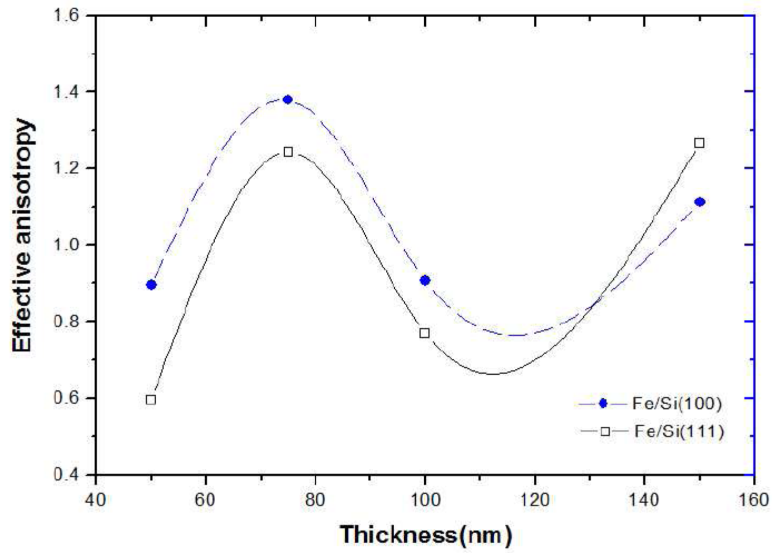

Fig. 7. Thickness dependence of the effective anisotropy in Fe/Si

5. Summary

The Fe films through evaporation technique grown on Si substrates and the structural and magnetic proprieties of them were studied due to thickness varying. The effects of film thicknesses on structure and magnetic anisotropy were studied in ultrathin films grown. The rms estimated between 0.5−1.5 and the rms slope between 0.02−0.06 with 45° texture direction for Fe films. HT-XRD pattern shows formation of β-$FeSi_2$ after annealing at 700°C and indicate obvious effects on the texture of the FeSi alloy. MFM images also reveal stripe domain structure for the 100 nm thick Fe on Si and various magnetization behaviors have been discussed. Hysteresis loops show good ferromagnetic characteristics of grown samples and also the obtained effective anisotropy show oscillation for Si substrates, when the grown films thicknesses are increased.

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