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The Influence of Thermal Annealing on Magnetostatic Properties of thin Ni Films

E.E. Shalyguina[1], Chong-Oh Kim[2*], Cheol Gi Kim[2], and JungHwa Seo[2]

[1] *Physical Faculty, Moscow State University, 119899, Moscow, Russia*
[2] *Department of Materials Engineering, Chungnam National University, Daejeon 305-764, Korea*

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The magnetostatic properties of the as-deposited and annealed at T = 300 and 400 °C Ni films were investigated employing both magneto-optical magnetometer and VSM. The Ni films of 50~200 nm thicknesses were prepared by DC magnetron sputtering technique. The strong influence of annealing temperature on magnetostatic properties of the studied samples was discovered. For the annealed Ni films, the increase of the coercivity H_C (up to 4 times) in comparison with that of as-deposited samples was revealed. The obtained results were explained by using crystallographic structural data of the samples.

Key words : Coercivity, Hysteresis loop, Magnetic film, Magneto-optical effect

1. Introduction

The investigation of low-dimensional magnetic structures has attracted considerable interest of researches for the last decade due to their enormous potential in technical applications and scientific curiosity in physical properties. Magnetic thin films (MTF) are the sample of two-dimensional solids because its thickness is significantly smaller than two others dimensions. MTF exhibit unique physical properties, which allow to use them in the form of useful inventions as a variety of active and passive microminiaturized components and devices [13], magnetic memory devices [4-6] interference filters, reflection and antireflection coating and so on [7, 8].

At the last years, the significant progress in the technology of the preparation of MTF has been achieved. That intensified the investigation of MTF, such as the study of the influence of the thickness, composition and crystallographic structure of MTF on its magnetic properties. Some results of already performed investigations have allowed to decide a set problem of physics of MTF. In particular, the notion about an influence of the interface between the magnetic film and the substrate on kinetic, magnetic and magneto-optical properties has been expanded significantly. Effects of grain morphology and grain crystallographic orientation of an underlayer on magnetic properties of MTF have been investigated in detail (see, for example [9]). The influence of microstructure and thickness of nonmagnetic layer (Ni, Zr, Ta, Al, Mo, Pt, Pd) on magnetic properties of Fe and Co films has been studied [10-13]. At the same time, the magnetic properties of the Ni films were investigated somewhat (see, for example [14-17], but the influence of annealing on their magnetic properties is practically unexplored.

In this article we presented results on the investigation of the magnetostatic properties of the as-deposited and annealed at temperature T = 300 and 400 °C Ni films. The variations of the magnetic properties are analyzed as function of the film thickness, microstructure and surface roughness.

2. Experimental

Series of Ni films were deposited on glass substrates at the room temperature by DC magnetron sputtering technique under a base pressure of less than 10^{-8} Torr and an argon gas pressure of 1×10^{-3} Torr. The film thickness in the every series was varied from 50 to 200 nm. To avoid oxidation, the films were covered by a 10-nm carbon layer. The series of the Ni films with the different thickness were annealed at 300 and 400 °C for 1h in vacuum.

The structural investigations of the examined samples were performed by X-ray diffraction analysis (XRD). The X-ray measurements were performed by using CuKα

*Corresponding author: Tel: +82-42-822-6233,
e-mail: magkim@cnu.ac.kr

radiation in Bragg-Brentano configuration with a graphite monochromator in diffracted beam. The surface structure of the Ni films was investigated by the atomic force microscope (AFM).

The volume magnetic characteristics of the samples were measured by a vibrating sample magnetometer (VSM). The measurements of near-surface hysteresis loops of Ni films were carried out employing magneto-optical magnetometer (MOM). He-Ne laser with the 624-nm wavelength of the light was used in this experimental setup. The angle of the light incidence on the sample plane was equal to 60°.

The magneto-optical Kerr effects in the reflected light are known to be sensitivity to the magnetization up to a certain depth below the surface of a ferromagnet, called "a penetration depth of the light in media", t_{Pen}. According to the existing experimental data [13], the value of t_{Pen} for metallic materials does not exceed 10~30 nm in the $0.5 < \hbar\omega < 6$ eV photon energy range. The magneto-optical effects of the first-order approximation on the magnetization are employed to measure near-surface hysteresis loops and magnetization curves for the examined samples. For the most of ferromagnetic materials, the value of the magneto-optical signals (δ) is equaled to 10^{-4}~10^{-2}. Here $\delta = (I - I_O)/I_O$, where I and I_O are the intensities of the reflected light from the magnetized and nonmagnetized sample, respectively. To increase the sensitivity of the magneto-optical magnetometer, the modulation methods of the registration of magneto-optical signals are applied. In the given case, the modulation of the intensity of the incident light was performed by using a special chopper. The modulation frequency of the incident light was equal to 80 Hz. Moreover, the special light sensor, containing an analyzer and two light detectors (LD_1 and LD_2), was employed. The above sensor allows to separate the reflected beam from a sample into two rays, the intensity of which are registered by the light detectors LD_1 and LD_2. Signals of the light detectors LD_1 and LD_2 are measured by the lock-in amplifier, which has two inputs A, B to incorporate with the differential input ($A-B$).

Taking into account the peculiarities of the magneto-optical effects, hysteresis loops of the studied samples were measured by the Meridional Kerr effect. The relative position of analyzer and polarizer was such that at the absence of magnetic field, the light intensity, registered by LD_1 (I_{O1}) and LD_2 (I_{O2}), is identical. In this case, the differential input ($A-B$) measures the value $\Delta_O = I_{O1} - I_{O2}$, equaled to zero. At the presence of the magnetic field H, applied to the studied sample, the rotation of the polarization plane, θ, in the reflected light arises due to the magneto-optical Kerr effect (MOKE). The sample magnetization M is proportional to the magnetic field H, and $\theta \sim M(H)$. As consequence of it, the intensity of both reflected light changes, and the differential input ($A-B$) measures the value $\Delta_1 \sim 2\theta(M)$. The special computer program provides a cyclic change of the magnetic field (from $-H$ to $+H$ and from $+H$ to $-H$), the acquisition of $\Delta_1(H) \sim 2\theta(M)$ to obtain hysteresis loops. All measurements were carried out at the room temperature.

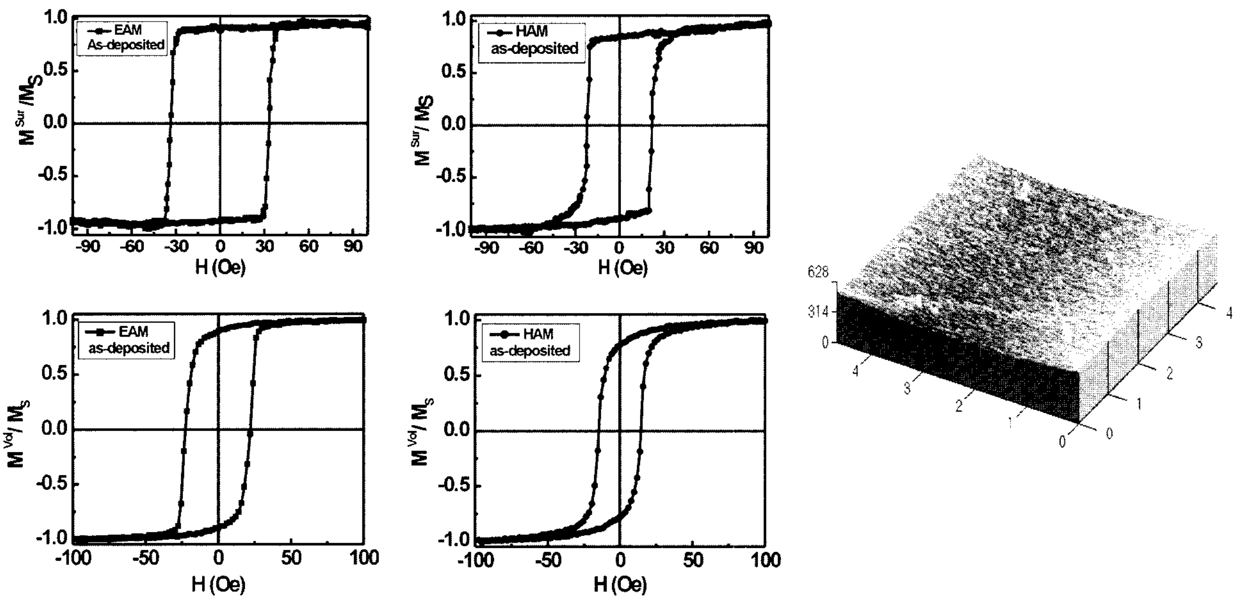

Fig. 1. Hysteresis loops, obtained for the as-deposited Ni film of the 70-nm thickness at two orientations of the in-plane magnetic field by the magneto-optical Kerr effect (MOKE) and vibrating sample magnetometer (VSM). The right panel shows AFM image of the film surface.

3. Results and Discussion

The hysteresis loops, measured for the studied Ni films by MOM and VSM, showed the strong influence of annealing temperature on magnetostatic properties, in particular, the coercivity H_C and the reduced remanent magnetization M_R/M_S (M_S is the saturation magnetization). For illustration, Figs. 1, 2 and 3 display hysteresis loops, obtained for the as-deposited and annealed at $T = 300$ and 400 °C Ni films of the 70-nm thickness at two orientations of the in-plane magnetic field. The right panels of these figures show AFM images of the film surfaces. The dependences of the near-surface and volume magnitudes of the coercivity and M_R/M_S on the Ni film thickness are presented in Figs. 4 and 5.

Analysis of the obtained data shows the following. The as-deposited and annealed at 300 °C Ni films exhibit an in-plane magnetic anisotropy, which intensifies in the

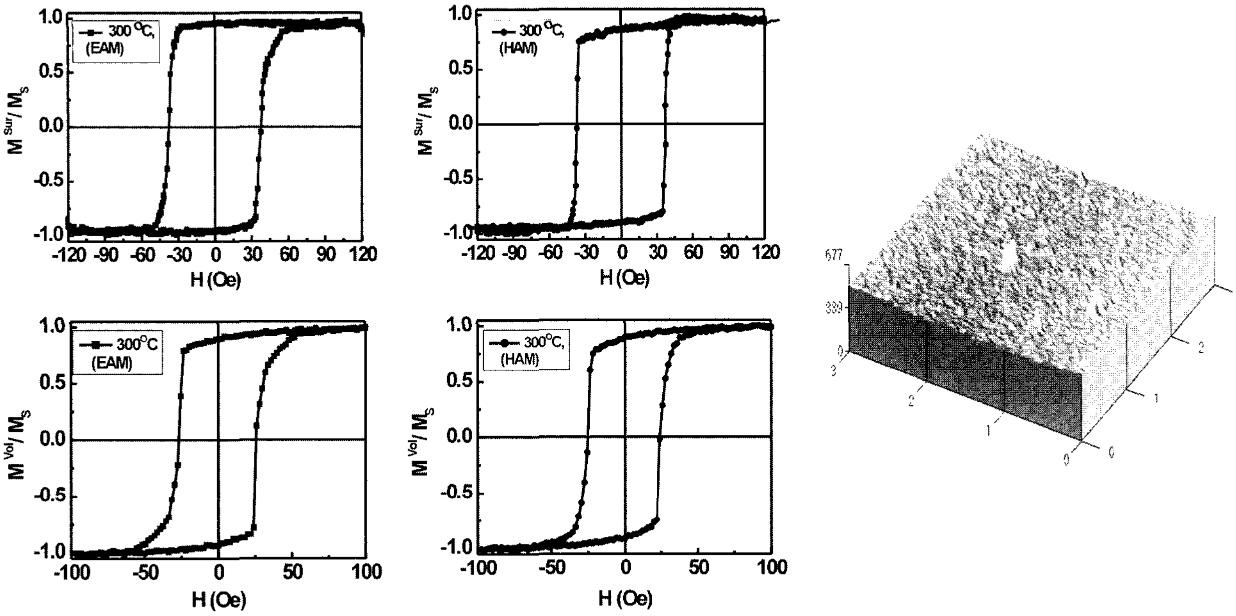

Fig. 2. Hysteresis loops, obtained for the annealed at $T = 300$ °C Ni film of the 70-nm thickness at two orientations of the in-plane magnetic field by MOKE and VSM. The right panel shows AFM image of the film surface.

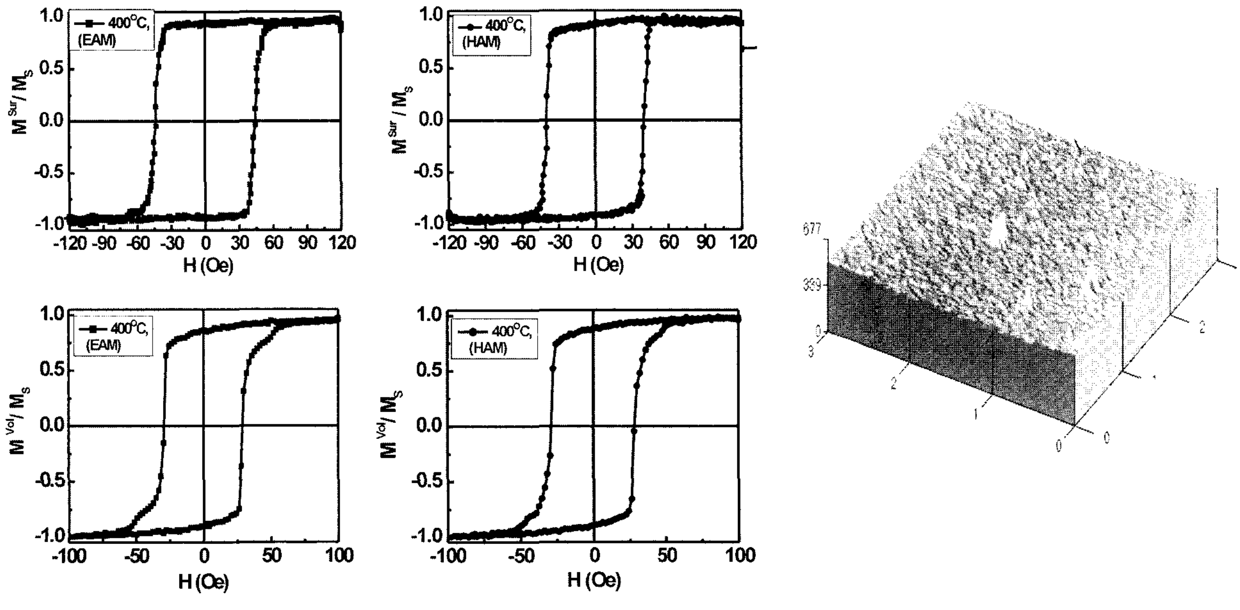

Fig. 3. Hysteresis loops, obtained for the annealed at $T = 400$ °C Ni film of the 70-nm thickness at two orientations of the in-plane magnetic field by MOKE and VSM. The right panel shows AFM image of the film surface.

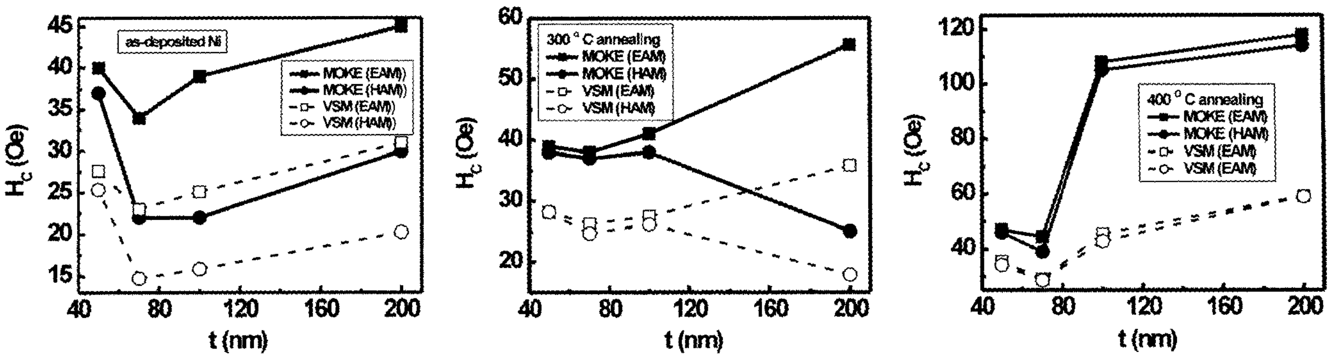

Fig. 4. The dependences of the near-surface (MOKE) and volume (VSM) magnitudes of the coercivity along the easy and hard axes of the magnetization (EAM and HAM) on the Ni film thickness.

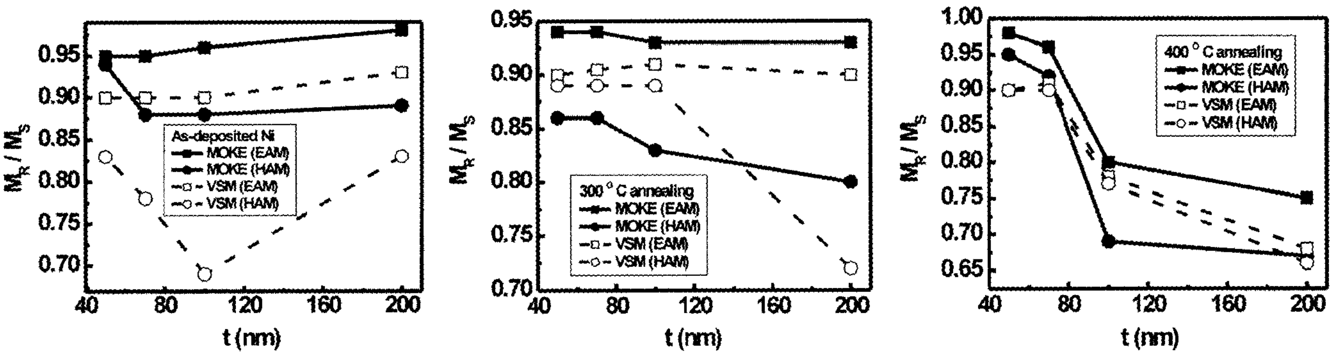

Fig. 5. The dependences of the near-surface (MOKE) and volume (VSM) magnitudes of the remanent magnetization along the easy and hard axes of the magnetization (EAM and HAM) on the Ni film thickness.

films of the 10 and 20-nm thickness. The direction of the easy axis of the magnetization (EAM) coincides with the orientation of the magnetic field, applied parallel to a substrate during the deposition processes. The hard axis of the magnetization (HAM) is perpendicular to the EAM. The nears-surface hysteresis loops along the EAM have nearly rectangular shape. With increasing the film thickness, the coercivity increases and the remanent magnetization $M^{Sur}{}_R/M_S$ has practically unchanged, enough high magnitudes (about 0.94~0.97). The thickness dependence of $M^{Vol}{}_R/M_S$ is similar but its values are about 0.9. For the above series of the Ni films, the coercivity and the remanent magnetization at the magnetic field along EAM and HAM was mostly distinctive for the Ni films of the 200-nm thickness.

For the annealed at 400 °C Ni films, the coercivity H_C at the magnetic field along for both the EAM and HAM has practically identical magnitudes. With increasing the Ni film thickness, the H_C values increase and the remanent magnetization decreases. Maximum increase of H_C was revealed for the annealed at T = 400 °C Ni film of the 200-nm thickness. In particular, the value of H_C at the magnetic field along the HAM is equal to 120 Oe that is larger (about 4 times) than that of the as-deposited sample.

The observed increase of the coercivity with increasing the film thickness and annealing temperature was explained by using XRD data. The whole of the studied Ni films were found to be polycrystalline with grain sizes comparable to the film thickness. At the present time it is proved that the magnetic-field behavior of thin films mainly depends on the competing parameters such as the grain size, a grain crystallographic orientation and domain wall pinning at the interfaces. For the examined films, the lines {111} were only observed in XRD spectra that showed the presence of the preferential (111) grain orientation parallel to the sample surface. With increasing annealing temperature, the intensity of the line {111} was revealed to increase

Table 1.

t_{Ni} (nm)	Intensity (a.u.) as-deposited	Intensity (a.u.) 300 °C annealing	Intensity (a.u.) 400 °C annealing
50	48	152	2130
70	180	2280	2400
100	260	3600	3680
200	1808	3760	4800

(see the Table 1) that is evidence of intensifying texture of the annealed Ni films.

It is known [18] that the better (111) textured samples result in larger coercivity. Moreover, according to reported data in [12, 13], the coercivity increases with enlarging magnetic film thickness that was attributed to the increase in the size of grains, forming film volume. We did observe such correlation between the magnetic and structural properties of the Ni films.

The increase of the near-surface magnitudes of H_C with increasing annealing temperature can also be ascribed to the enlarging near-surface roughness. According to AFM data, the near-surface roughness of the annealed Ni films intensifies. For example, for the as-deposited and annealed at T = 300 and 400 °C Ni films of the 70-nm thickness, the averaged (and maximum) size of roughness is equal to 0.45 (0.65), 0.53 (1) and 0.68 (1.07) nm, respectively.

At last, from Figs. 4 and 5 one can see that the near-surface and volume magnitudes of H_C and M_R/M_S are distinct. A comparison of the obtained data shows that $H^{Sur}{}_C > H^{Vol}{}_C$ and $M^{Sur}{}_R/M_S > M^{Vol}{}_R/M_S$. Such difference of the near-surface and volume characteristics is typical for the magnetic films of the foregoing thickness [19]. On the analogy of the existing data, this fact can be explained by both the distinguishing domain structure of the near-surface area and the film volume. The presence of the roughness at the film surface can also cause this distinction.

4. Conclusion

The influence of thermal annealing on the magnetostatic properties of the Ni films of 50~200 nm thickness was studied. The significant increase of the coercivity for the annealed samples was revealed. The observed variations of the magnetic properties as functions of thickness and annealing temperature were explained by the structural changes of the annealed Ni films in comparison with the as-deposited ones. The marked distinction of the near-surface and volume magnetic characteristics of the Ni films was discovered. That was ascribed to both the distinguishing domain structure of the near-surface area and the film volume and the existing roughness at the film surface. The obtained new experimental data can promote further designing multilayered systems for modern devices of spin microelectronics.

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