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The influence of annealing temperature on magnetic and magneto-optical properties of Ni films

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Results on the investigation of the magnetic and magneto-optical (MO) properties of the as-deposited and annealed (at T_{ann} = 300 and 400 °C) Ni films of 50-200 nm thickness are presented. The measurements of hysteresis loops were carried out employing both VSM and magneto-optical method. Spectral dependencies of the Transverse Kerr Effect (TKE) were measured for the 1.4 - 6 eV energy range of the incident light. The strong influence of annealing temperature on the magnetic and MO properties of the Ni films was discovered. For the annealed Ni films, the coercivity H_C increases (about 4 times) and the remanant magnetization decreases (about 1.3 times) in comparison with those of the as-cast samples. The distinction of the near-surface and volume magnetic characteristics was detected that was ascribed to the distinguishing domain structure of the near-surface layers and the film volumes. The observed variations of the magnetic properties with increasing the film thickness and annealing temperature were explained by the change of crystalline structure of the Ni films. With increasing T_{ann}, TKE spectra of the Ni films are modified.
Key words: Coercivity; Kerr effect; Magneto-optical properties; Ni films

1. INTRODUCTION

The investigation of low-dimensional magnetic materials 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 two-dimensional solids because its thickness is significantly smaller than two other dimensions. MTF exhibit unique physical properties, which allows us to use them in the form of useful inventions as a variety of active and passive microminiaturized components and devices [1-3], magnetic memory devices [4-6] interference filters, reflection and antireflection coating [7, 8], and so on. At the last years, the significant progress in the technology of the preparation of MTF has been achieved that intensified the investigation of MTF. Some results of already performed investigations have allowed us 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 the magnetic properties of MTF have been investigated in details (see, for example [9]). The influence of microstructure and thickness of nonmagnetic layer (Ni, Zr, Ta, Al, Mo, Pt, Pd) on the 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 an annealing on their magnetic and magneto-optical properties is practically unexplored.

In this article we presented results on the investigation of the magnetic and magneto-optical properties of the as-deposited and annealed at temperature T = 300 and 400 °C Ni films. The variations of the studied 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 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 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 surface structure of the Ni films was studied by the atomic force microscope (AFM).

The volume magnetic characteristics of the samples were measured by a vibrating sample magnetometer (VSM). The near-surface hysteresis loops of Ni films were measured employing the magneto-optical method (MOM). The He-Ne laser with the 624-nm wavelength of the light was used in this experimental set-up.

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 ferromagnetics, 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. In the given case t_{Pen} is 20 nm.

Spectral dependencies of the Transverse Kerr Effect (TKE) were measured for the 1.4 - 6 eV energy range of the incident light.

All measurements were carried out at the room temperature.

RESULT AND DISCUSSION

The hysteresis loops, measured for the studied Ni films by MOM and VSM, showed the strong annealing temperature dependence of magnetostatic properties, in particular, of the coercivity H_C and the normalized magnetization M_R/M_S (M_R and M_S are remanent and saturation magnetization, respectively). For illustration, Figs. 1, 2 and 3 display hysteresis loops, obtained for the as-deposited and annealed 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 dependencies 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.

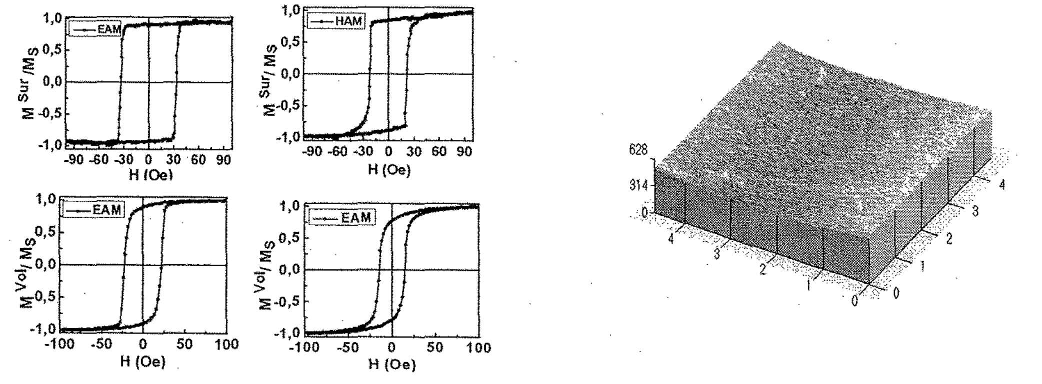

Fig. 1. Hysteresis loops, observed for the as-deposited Ni film of the 70-nm thickness at the in-plane magnetic field, applied parallel to the easy and hard axis of the magnetization ((EAM) and (HAM)), by the magneto-optical Kerr effect (MOKE) and vibrating sample magnetometer (VSM). The right panel shows AFM image of the film surface.

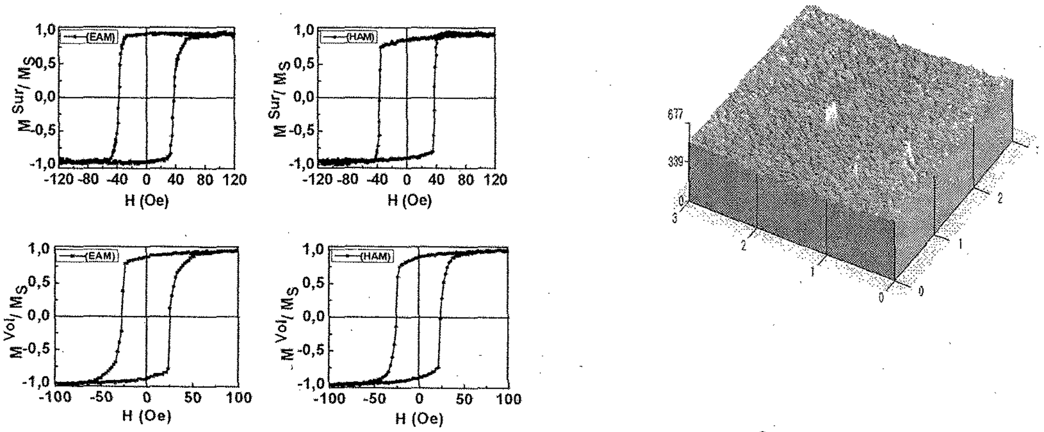

Fig. 2. Hysteresis loops, observed by MOKE and VSM for the annealed at $T = 300\ ^{O}C$ Ni film of the 70-nm thickness at the in-plane magnetic field, applied parallel to EAM and HAM. The right panel shows AFM image of the film surface.

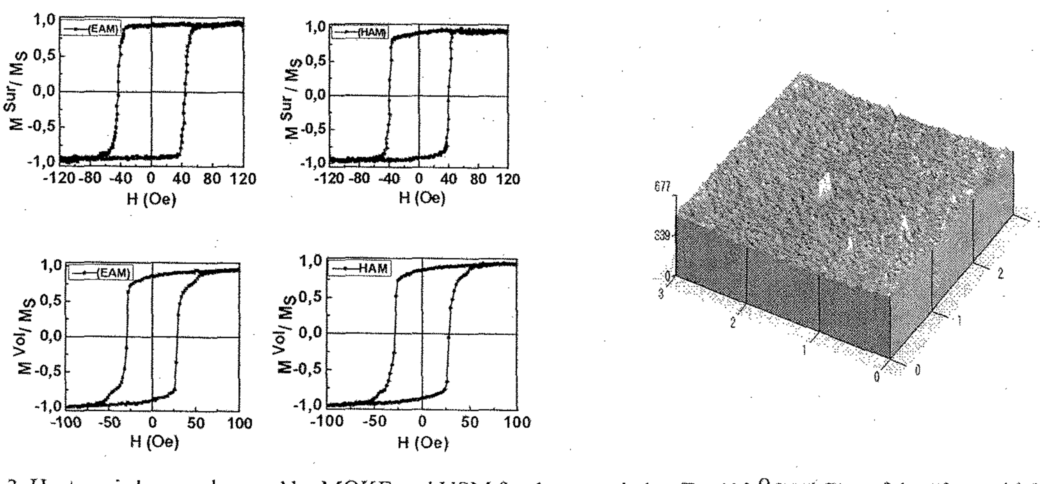

Fig. 3. Hysteresis loops, observed by MOKE and VSM for the annealed at $T = 400\ ^{O}C$ Ni film of the 70-nm thickness at the in-plane magnetic field, applied parallel to EAM and HAM. The right panel shows AFM image of the film surface.

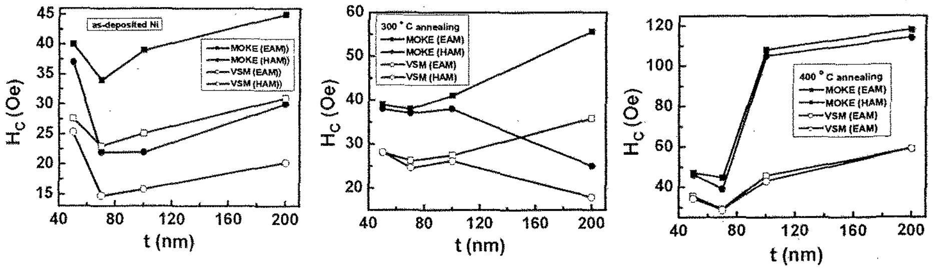

Fig. 4. The dependencies of the near-surface (MOKE) and volume (VSM) magnitudes of the coercivity along the easy and hard axes of the magnetization on the Ni film thickness.

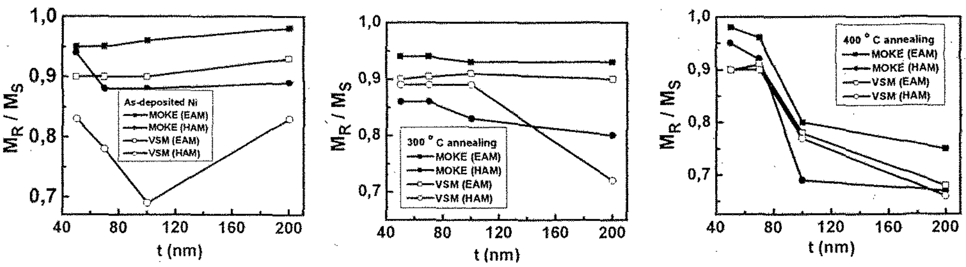

Fig. 5. The dependencies of the near-surface (MOKE) and volume (VSM) magnitudes of the remanent magnetization along the easy and hard axes of the magnetization (EAM and HAM) on the Ni film thickness.

Analysis of the obtained data shows the following. The as-deposited and annealed at 300 ^{O}C Ni films exhibit an in-plane magnetic anisotropy, which intensifies in the films of the 10 and 20-nm thickness. The direction of the easy axis of the magnetization (EAM) coincides with the orientation of the external 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 $M^{Sur}{}_R/M_S$ keeps practically unchanged, enough high magnitudes (about 0.94 - 0.97). The thickness dependence of $M^{Vol}{}_R/M_S$ is similar to that of $M^{Sur}{}_R/M_S$ 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 ^{O}C Ni films, the coercivity H_C at the magnetic field along both the EAM and HAM has practically identical magnitudes. With increasing the Ni film thickness, the H_C increases and the remanent magnetization decreases. Maximum increase of H_C was revealed for the annealed at T = 400 ^{O}C Ni film of the 200-nm thickness. In particular, the value of H_C under 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. All 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 factors such as the grain size, a grain crystallographic orientation and domain wall pinning at the interfaces. For the examined films, the lines {111} were observed only in XRD spectra, which 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 (see table 1), which 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, which 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 ^{O}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 thickness dependence of the near-surface and volume magnitudes of H_C and M_R/M_S are different. 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 with the thickness about 50-200 nm [19]. On the analogy of the existing data, this fact can be explained by the different domain structures of the near-surface area and the film volume. The presence of the roughness at the film surface can also cause this distinction.

Fig. 6 shows the dependencies of TKE on the energy of the incident light, obtained for the studied Ni films. The angle of the light incidence on the sample was equal to 65^{O}. From Fig. 6 one can see that the shape of TKE spectra is practically identical for the examined samples. The maximum magnitudes of TKE ($\delta_{TKE}{}^{max}$) for the whole Ni films are observed near $\hbar\omega$ = 3.7 eV. $\delta_{TKE}{}^{max}$ is equaled to 4.6x10^{-3}, 3.9x10^{-3} and 3.6x10^{-3} for

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

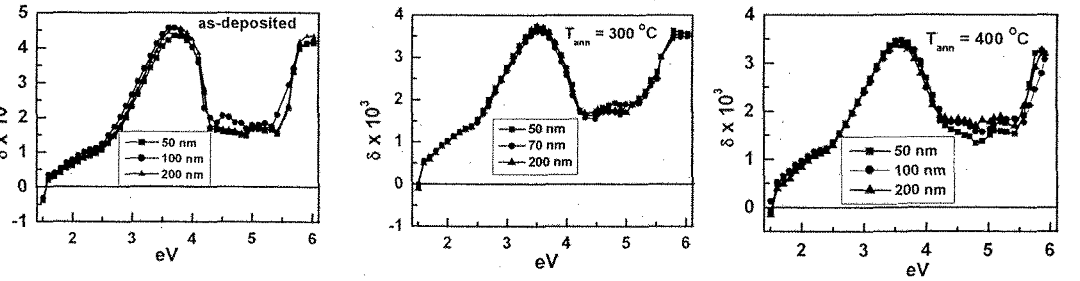

Fig. 6 Spectra of TKE obtained for the as-deposited and annealed Ni films.

as-deposited and annealed at 300 and 400 °C Ni films, respectively. The magnitudes of TKE decrease with increasing the annealing temperature. This fact can be explained by the following. According to VSM data, the values of M_S of the annealed at 300 and 400 °C Ni films decreases in 1.1 and 1.2 times, respectively, with respect to M_S of the as-deposited samples. It is known that magneto-optical effects within the first-order approximation have linear dependence on the magnetization ($\delta \propto M$). As a result, the decrease of M_S in the annealed samples causes the decrease of TKE.

CONCLUSION

The influence of thermal annealing on the magnetic and magneto-optical 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. This fact was explained by both the distinguishing domain structures of the near-surface layer and the film volume and the existing roughness at the film surface. The discovered decrease of TKE with increasing the annealing temperature was explained by the decrease of M_S in the annealed Ni films. The obtained new experimental data can promote further designing multilayered systems for modern devices of spin microelectronics.

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