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Competing magnetic anisotropies in obliquely deposited thin permalloy film

B.A. Belyaev [a,b,c], A.V. Izotov [a,b], P.N. Solovev [a,*]

[a] Siberian Federal University, 79, pr. Svobodnyi, Krasnoyarsk 660041, Russia
[b] Kirensky Institute of Physics, Siberian Branch of the Russian Academy of Sciences, 50/38, Akademgorodok, Krasnoyarsk 660036, Russia
[c] Reshetnev Siberian State Aerospace University, 31, pr. Imeni Gazety “Krasnoyarskii Rabochii”, Krasnoyarsk 660014, Russia

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ABSTRACT

Distribution of the magnetic anisotropy in thin film prepared by thermal vacuum oblique deposition of permalloy with small off-normal angle of incident in the presence of an external magnetic field has been studied by ferromagnetic resonance technique. On local area of the sample, a mutual compensation of near orthogonal in-plane uniaxial magnetic anisotropies induced by oblique deposition and by applied magnetic field has been found. Moreover, in addition to the uniaxial (twofold) magnetic anisotropy, fourfold and sixfold magnetic anisotropies have been observed in the sample. To explain the obtained high-order anisotropies, we assumed that the sample has exchange coupled adjacent regions or phases with different parameters of magnetic anisotropy. The results of the micromagnetic analysis of a two-layer model of the sample confirm the hypothesis.

1. Introduction

Magnetic anisotropy is the fundamental property of thin films that has a strong impact on their static and dynamic magnetic behavior [1,2]. Generally, the intrinsic magnetic anisotropy of a thin polycrystalline ferromagnetic film is a sum of effective anisotropies originating from various mechanisms such as elastic stress, microstructure inhomogeneity, atomic pair ordering, and others [3]. Understanding of the role of each mechanism in the formation of the resulting anisotropy is crucial for producing samples with controllable magnetic properties designed to meet requirements of modern micro- and nano-electronic technologies [4].

Oblique deposition of atoms on a substrate is a well-known method for producing samples with well-defined uniaxial anisotropy [5,6]. Magnetic anisotropy arises as a consequence of a dipolar interaction of inhomogeneous column-like microstructure that develops in films because of self-shadowing effect [5–8]. Oblique deposition is used widely to produce multilayer films [9,10] and exchange bias systems [11] with accurate control of uniaxial anisotropy in individual layers. Note that most studies on magnetic anisotropy induced by oblique deposition have only been carried out for relatively large off-normal angles of incidence. However, we have recently reported that oblique deposition even for very small incident angles ($\sim 2^\circ$) strongly influences the magnetic characteristics of a thin permalloy film [12]. In the study, it was also shown that in the low-incidence angle deposition film the magnetic anisotropy that originates from oblique deposition is an important, but not necessarily dominant contribution in the resulting anisotropy.

The purpose of the present study is to explore the competitive relation between two close-in-value magnetic anisotropies induced by (i) oblique deposition with low-incidence angle and (ii) by magnetic field applied during sample growth. The central focus of our study is the effect of the anisotropies compensation obtained on local area of the thin permalloy film when their easy axes are mutually orthogonal. Our particular interest is related to the appearance of high-order magnetic anisotropies observed near the compensation point.

2. Experimental details

A sample was produced by thermal vacuum evaporation of $Ni_{82}Fe_{18}$ on a polished glass $10 \times 10 \times 0.5$ mm size substrate. The base pressure was lower than 10^{-6} mbar and the deposition rate was 1 nm/s. The distance between the vapor source and the substrate was 240 mm. The substrate was tilted so that the deposition beam struck the surface at a small angle with respect to the film normal. As illustrated in Fig. 1a, because of the conical trajectory of the deposited atoms, the incidence angle α changes gradually within the substrate from 7° to 9.2° along the x axis of the film

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[*] Corresponding author.
E-mail address: platon.solovev@gmail.com (P.N. Solovev).

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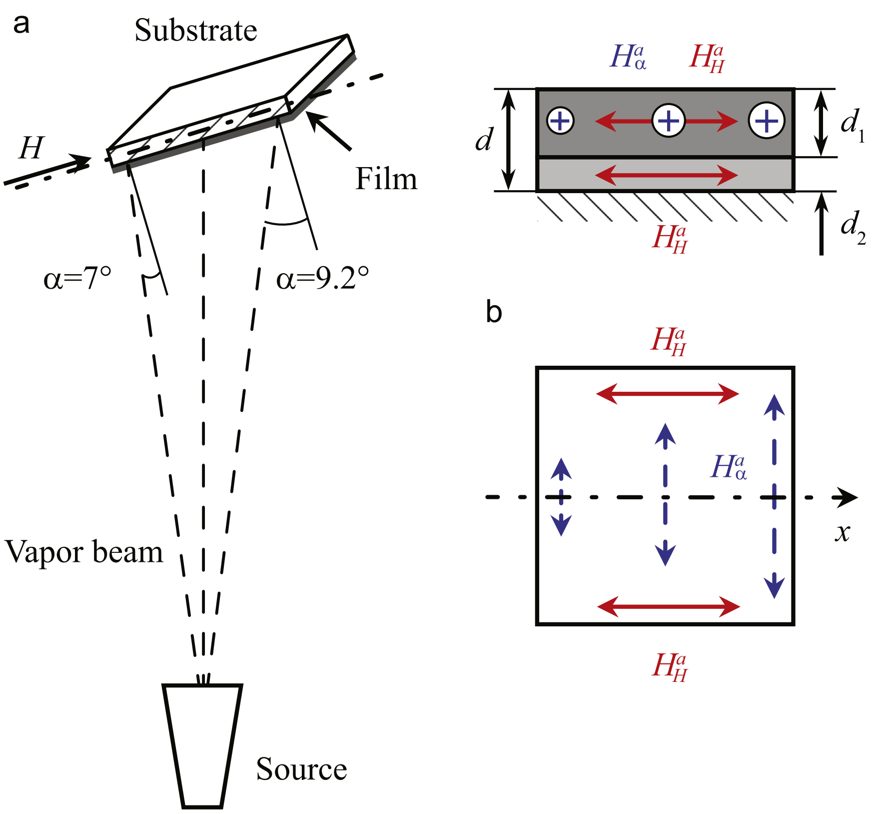

Fig. 1. (a) Sketch of the film deposition in the applied magnetic field H. (b) The bilayer model of the film with uniaxial anisotropies induced by magnetic field H^a_H and oblique deposition H^a_α.

depending almost linearly on the x coordinate. During the deposition, an orienting external magnetic field H=200 Oe was applied on the film plane. The direction of the magnetic field was set in such a way that the anisotropies induced by the field (H^a_H) and the oblique deposition (H^a_α) were mutually orthogonal. X-ray fluorescence analysis showed that the thickness of the sample d was 61 nm and its composition was $Ni_{83.7}Fe_{16.3}$.

Magnetic properties were analyzed by the scanning spectrometer of ferromagnetic resonance (FMR) [13]. The microstrip resonator fabricated on a dielectric substrate was used as a sensor in the spectrometer. The measuring hole was etched in the ground plane of the resonator near the antinode of high-frequency magnetic field. The hole diameter (~1 mm) determined the locality of measurements. Resonant absorption of microwaves by an investigated part of the magnetic film was registered by the modulation method through the change of the resonator quality factor during the sweeping of the static magnetic field. Because of the large filling factor of the microstrip resonator, the spectrometer had high sensitivity. The microwave pump frequency was 2.274 GHz for all measurements. Angular dependences of FMR field $H_R(\varphi_H)$ and linewidth $\Delta H(\varphi_H)$ were measured with 1 mm step along the x axis of the film, which was parallel to the external magnetic field.

For detailed analysis of the experimental data, we have developed a technique to extract information about high-order magnetic anisotropies from measured angular dependences of the resonance field. The analysis is based on the expression of the magnetic anisotropy energy in a form of a Fourier expansion versus in-plane azimuthal magnetization angle φ

$$F^a(\theta,\varphi) = \sum_n A_n(\theta)\cos n(\varphi-\varphi_n^a), \tag{1}$$

where θ means the angle between the magnetization and the normal to the film plane, $H_n^a = n^2 A_n(\pi/2)/M_s$ and ϕ_n^a are effective field and direction of n-order in-plane magnetic anisotropy, and M_s is the saturation magnetization. Taking into account the Zeeman energy, the shape anisotropy of the film, and the uniaxial perpendicular anisotropy with constant $K_\perp$, the free energy density can be written as

$$F(\theta,\varphi) = -M_s H\cos(\varphi-\varphi_H)\sin\theta + 2\pi M_s^2\cos^2\theta - K_\perp\cos^2\theta + F^a(\theta,\varphi). \tag{2}$$

In low-dimensional systems such as thin films, a shape anisotropy energy is usually the dominant term in the total magnetic anisotropy energy. The shape anisotropy is the main reason of in-plane orientation of the magnetization in the sample. The reorientation of the spontaneous magnetization from the film plane to the normal because of the surface anisotropy is possible only for ultrathin films with thicknesses of a few atomic layers [14]. Therefore, when the film is magnetized by the in-plane external magnetic field, the equilibrium angle θ equals $\pi/2$.

Using the Smith and Suhl formula [15,16], the ferromagnetic resonance equation and equilibrium condition can be written as follows:

$$\left[H_R\cos(\varphi_M-\varphi_H)+\frac{F^a_{\varphi\varphi}}{M_s}\right]\times\left[H_R\cos(\varphi_M-\varphi_H)+4\pi M_{eff}+\frac{F^a_{\theta\theta}}{M_s}\right] - \frac{F^{a2}_{\theta\varphi}}{M_s^2} = \left(\frac{\omega_0}{\gamma}\right)^2, \tag{3}$$

$$H_R\sin(\varphi_M-\varphi_H) + F^a_\varphi/M_s = 0, \tag{4}$$

where $f_0=\omega_0/2\pi$ is the microwave pump frequency, γ is the gyromagnetic ratio and M_{eff} is the effective magnetization ($4\pi M_{eff} = 4\pi M_s - 2K_\perp/M_s$). The partial derivatives of $F^a_{\phi\phi}$, $F^a_{\theta\theta}$, $F^a_{\theta\phi}$, and F^a_ϕ have to be taken at the equilibrium position of the