01,05,13

In-plane magnetic anisotropy and domain structure of FeNi films deposited in the presence of a magnetic field of various configurations

© A.V. Svalov, V.E. Ivanov, S.V. Andreev, V.N. Lepalovskij, A.A. Feshchenko, E.V. Kudyukov, I.A. Makarochkin, G.V. Kurlyandskaya

Institute of Natural Sciences and Mathematics,
Ural Federal University named after the First President of Russia B.N. Yeltsin,
Yekaterinburg, Russia

E-mail: andrey.svalov@urfu.ru

Received April 17, 2023
Revised April 17, 2023
Accepted May 11, 2023

FeNi films in circular shape with 3 mm in diameter obtained by magnetron sputtering in the presence of a constant magnetic field of various configurations are studied. The presence of a field created by a permanent magnet with a diameter of 1.2 mm, the magnetization of which is oriented perpendicular to the plane of the substrate, leads to the formation of a vortex-like magnetic structure in the film, characterized by diffuse domain walls.

Keywords: thin magnetic films, induced magnetic anisotropy, magnetic domain structure, magnetron sputtering.

DOI: 10.21883/PSS.2023.06.56091.17H

1. Introduction

Thin magnetic films form the main working material of spintronics devices [1]. One of the main functional parameters of such materials is magnetic anisotropy. Some applications require pronounced uniaxial magnetic anisotropy in plane or perpendicular to the film plane, others, on the contrary, require no magnetic anisotropy to enhance the magnetic softness of the film elements [1,2]. The main ways of forming induced magnetic anisotropy in the film plane are by oblique sputtering and film deposition in the presence of a magnetic field oriented in the substrate plane [2–4]. Film sputtering in the presence of a magnetic field perpendicular to the substrate plane can increase perpendicular magnetic anisotropy, the occurrence of which is generally due to the film's microstructure, namely the columnar structure [5–7]. The reduction of magnetic anisotropy in the sample plane is most often achieved by exposing the deposited film to a magnetic field rotating in the substrate plane or by subsequent additional thermomagnetic treatments [8,9]. In addition, this problem is solved by matching the geometric shape of the objects [10]. The size of these elements is usually in the range of fractions to tens of microns. Nevertheless, there is also interest in millimeter [11] scale objects. Data on the influence of the vertical magnetic field in the sputtering on the formation of magnetic anisotropy in the film plane are very sparsely reported in the literature [12]. The present work presents the results of studies of in-plane magnetic anisotropy and domain structure features of FeNi film elements deposited in the presence of magnetic fields of different configuration, including the one generated by a permanent magnet, magnetization of which was oriented perpendicular to the substrate plane.

2. Technique of studies

$Fe_{20}Ni_{80}$ films of 40 nm thickness were deposited on glass substrates by magnetron sputtering of the target in an argon atmosphere. Sputtering was done through a metal mask, making it possible to form elements in the form of a circle of 3 mm in diameter. The films were deposited either in the absence of an external magnetic field (samples of type F1) or in the presence of a constant magnetic field of 200 Oe oriented in the substrate plane (F2). In addition, elements deposited in the presence of a magnetic field generated by a permanent magnet of diameter 1.2 mm whose magnetization was oriented perpendicular to the substrate plane (F3) were obtained. The perpendicular field strength on the surface of the magnet was 400 Oe.

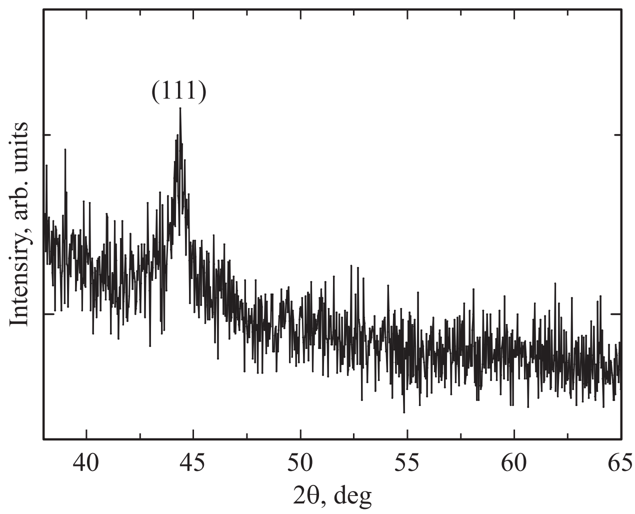

Figure 1. Diffraction pattern of F1 type sample.

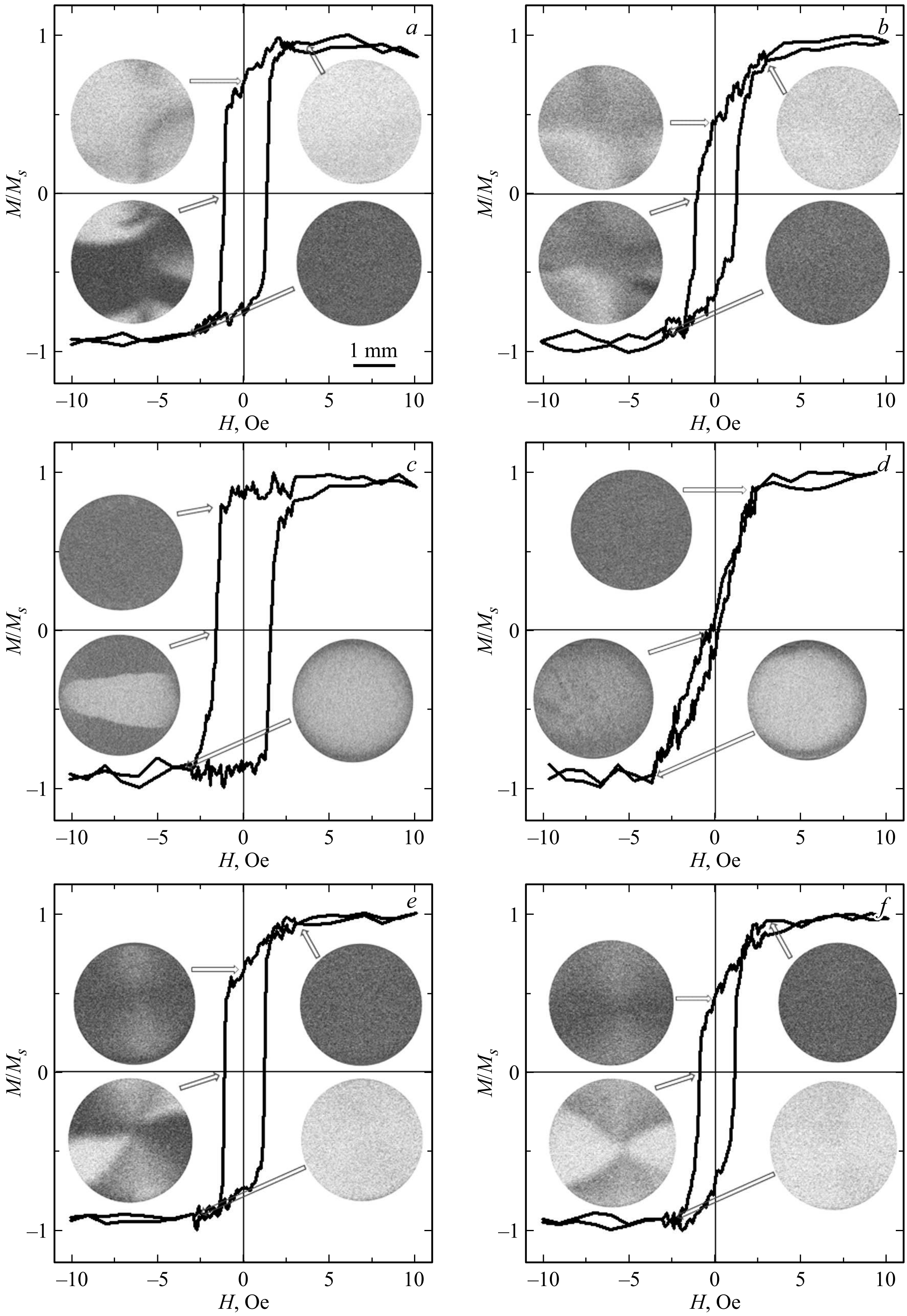

Figure 2. Magneto-optical hysteresis loops and corresponding images of magnetic domain structure obtained in two mutually perpendicular directions for samples F1 (*a, b*), F2 (*c, d*) and F3 (*e, f*). For images of the domain structure: the axis of application of the measuring magnetic field is oriented horizontally.

The structure of the film samples was studied using a Bruker D8 Advance X-ray diffractometer and a Ntegra Prima atomic force microscope. The magnetic properties of the samples were studied using the Lake Shore Cryotronics vibrating magnetometer and the Evico magneto-optical Kerr microscope.

3. Produced findings and discussion

The different film preparation conditions had no noticeable effect on the structural features of the films. The crystalline FCC structure of all samples was characterized by the texture (111). Fig. 1 shows an example of an F1 sample diffraction pattern. The average crystallite size determined using the Scherrer formula was 10 nm. The RMS surface roughness amplitude R_{rms} for all FeNi films did not exceed 0.3 nm.

Magneto-optical (MO) hysteresis loops were measured for all three sample types at different orientations of the magnetic field in the sample plane. The elements were found to have varying degrees of magnetic anisotropy in the film plane. For F2 samples, a pronounced induced uniaxial magnetic anisotropy was observed, with easy magnetization axis (EMA) coinciding with the axis of the magnetic field applied during film deposition. The MO hysteresis loop measured along the EMA had a characteristic rectangular shape, and the sample remagnetization process was carried out by moving the domain boundaries (Fig. 2, *c*). The MO-loop measured at right angles to the EMA was characterized by a markedly lower hysteresis, the smooth change in the MO-contrast being evidence of remagnetization of the film due to rotation of the spontaneous magnetization vector (Fig. 2, *d*). The presence of uniaxial magnetic anisotropy is also confirmed by the angular dependence of the coercive force H_c, where θ — the angle between the measuring field direction and the EMA (Fig. 3, *b*). The magnitude of the magnetic anisotropy field H_a was 3.5 ± 0.5 Oe. The nature and possible mechanisms of this so-called *M*-induced anisotropy in polycrystalline films 3*d*- and their alloys are well studied [13].

In-plane angular MO measurements revealed uniaxial magnetic anisotropy also for F2 samples deposited in the absence of an external magnetic field. The criterion for determining the EMA orientation was the highest value of residual magnetization, as values H_c for the EMA and the perpendicular direction differed by only 0.1 Oe (Fig. 2, *a, b*). However, the angle dependence H_c confirms the presence of weak uniaxial anisotropy (Fig. 3, *a*; angle values 0° and 180° correspond to the measurement field direction along the EMA). The probable cause for this magnetic anisotropy is the presence of a laboratory magnetic field in the substrate holder area, the magnitude of which proved sufficient to orient the magnetization of the growing film.

For type F3 samples, the differences in the shape of the hysteresis loops measured in the conditional „easy“ and „hard“ magnetization directions are even less pronounced (Fig. 2, *e, f*). The angular dependence of the coercive force

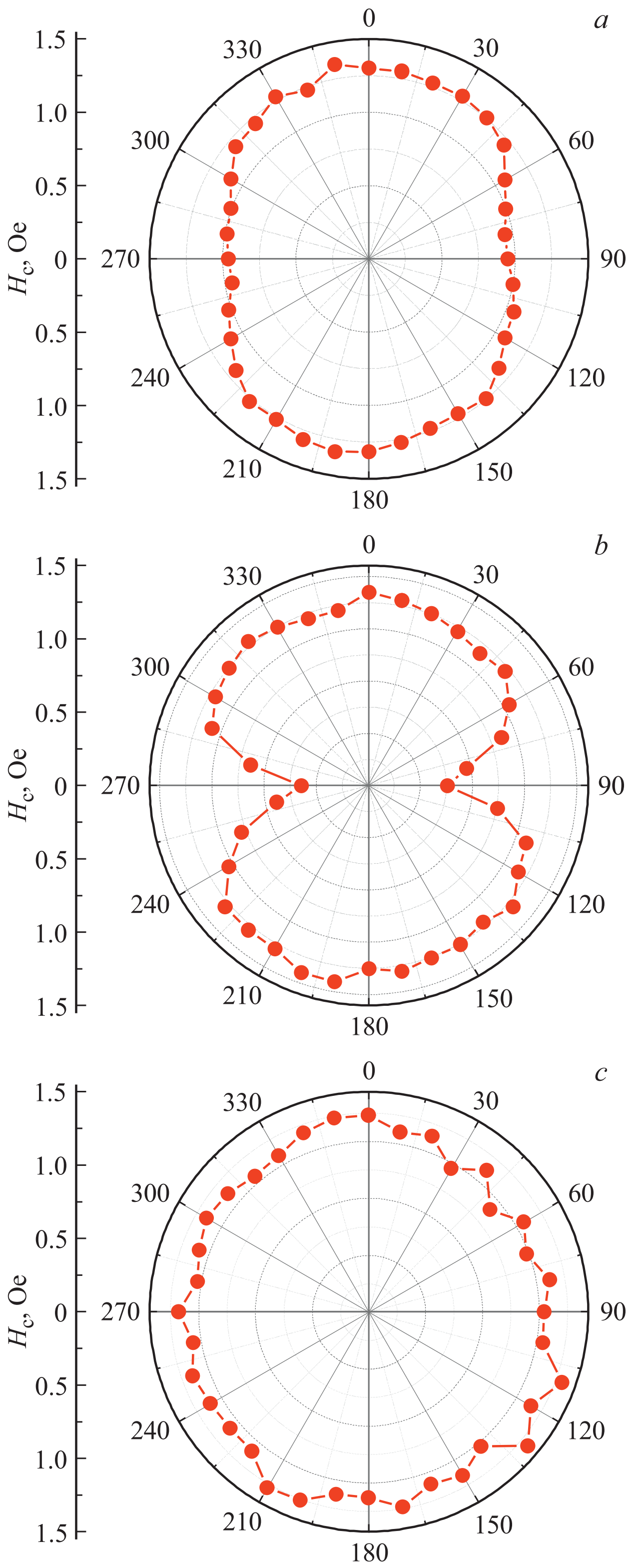

Figure 3. Angular dependence of the coercive force for samples F1 (*a*), F2 (*b*) and F3 (*c*).

has an almost isotropic appearance (Fig. 3, *c*). The configuration of the domains and the weakly pronounced domain walls in fields close to the coercive force, (Fig. 2, *e, f*) suggest

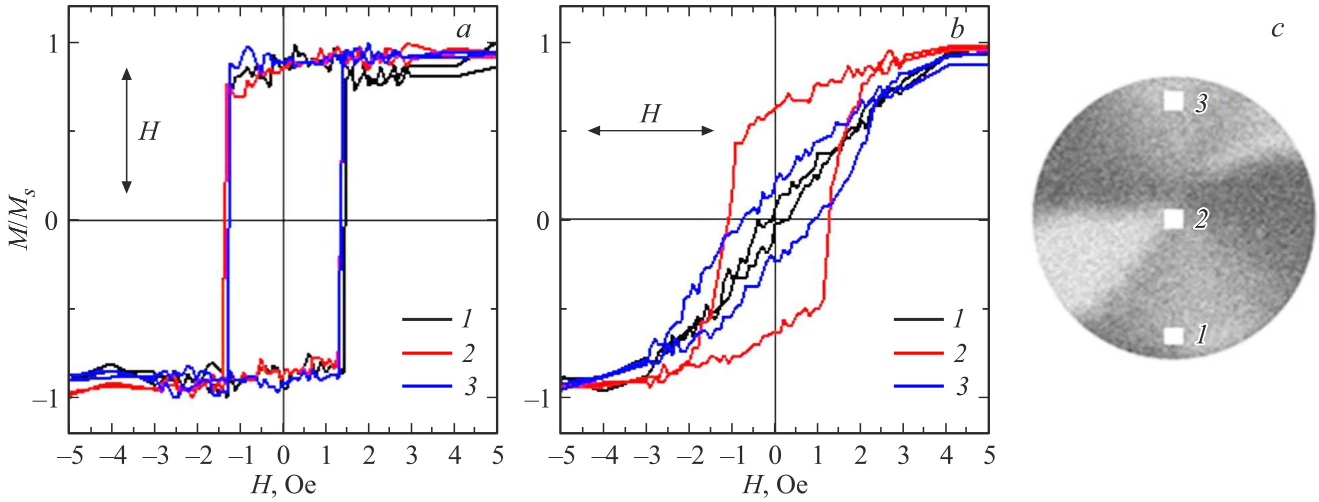

Figure 4. Local MO hysteresis loops for F3 type sample. The loop number corresponds to the point number on the sample (c). The arrows on (a) and (b) show the orientation of the axis, along which the measuring field was applied, relative to the sample (c).

a vortex-like magnetic state [9,14,15] occurring in this type of samples.

Obviously, a magnet field of 400 Oe is not enough to line up the magnetization of the growing FeNi film perpendicular to its surface. However, the horizontal component of the magnet field is quite sufficient to orient the magnetization in the film plane. The sputtering geometry defines the radial distribution of the horizontal component of the magnet's field. Assuming M- the induced nature of the magnetic anisotropy formed in the film, a radial distribution of light magnetization axes in the sample plane can be expected. To test this assumption, local MO hysteresis loops were measured at three different points in the sample. The MO signal was recorded from a surface area of $200\,\mu\text{m} \times 200\,\mu\text{m}$, at each point, the measurements were made with the field orientation in the film plane along two mutually perpendicular axes (Fig. 4). It can be seen that with the field orientation along the sample radius, rectangular hysteresis loops were observed at all points. When the field orientation in the film plane is perpendicular to the sample radius, loops characteristic of sample remagnetization along the „hard“ magnetization direction were recorded at points *1* and *3*. The shape of the loop measured at point *2* is expected to approach rectangular. The lack of complete rectangularity of the loop is due to the measurement deviation of the point *2* from the center of the sample. Thus, the combination of the obtained hysteresis loops indicates that in F3 type samples, the local EMA are oriented along the sample radius.

4. Conclusion

In film cells $Fe_{20}Ni_{80}$ 3 mm in diameter, produced by magnetron sputtering in the presence of constant magnetic field of different configuration, induced magnetic anisotropy in the sample plane occurs. The orientation of the easy magnetization axis is determined by the orientation of the film's magnetization during deposition (M-induced anisotropy). The presence of a field generated by a permanent magnet of diameter 1.2 mm, whose magnetization is oriented perpendicular to the substrate plane, leads to the formation in the film plane of a radial distribution of axes of easy magnetization, which contributes to the formation of a vortex-like magnetic structure in the element.

Funding

This study was supported by grant No. 22-29-00980, provided by the Russian Science Foundation (https://rscf.ru/project/22-29-00980/.

Conflict of interest

The authors declare that they have no conflict of interest.

References

[1] A. Hirohata, K. Yamada, Y. Nakatani, I.-L. Prejbeanu, B. Diény, Ph. Pirro, B. Hillebrands. J. Magn. Magn. Mater. **509**, 166711 (2020).
[2] M.A. Milyaev, L.I. Naumova, T.A. Chernyshova, V.V. Proglado, N.A. Kulesh, E.I. Patrakov, I.Y. Kamensky, V.V. Ustinov. FMM **117**, *12*, 1227 (2016). (In Russian)
[3] B.A. Belyaev, A.V. Izotov, P.N. Solovev. Physica B **481**, 86 (2016).
[4] A.V. Svalov, I.A. Makarochkin, V.N. Lepalovskij, A.A. Pasynkova, A.A. Feshchenko, A.N. Gorkovenko, G.V. Kurlyandskaya. SPIN, 2240001 (2022).
[5] G.S. Kandaurova, V.E. Ivanov. Pis'ma v ZhETF **66**, *11*, 688 (1997). (in Russian).
[6] A.V. Svalov, E. Fernandez, A. Garcia-Arribas, J. Alonso, M.L. Fdez-Gubieda, G.V. Kurlyandskaya. Appl. Phys. Lett. **100**, 162410 (2012).

[7] A.S. Dzhumaliev, S.L. Vysotsky, V.K. Sakharov, FTT **62**, *12*, 2174 (2020). (in Russian).
[8] E. Fuchs, W. Zinn. J. Appl. Phys. **34**, 2557 (1963).
[9] R. Schäfer. J. Magn. Magn. Mater. **215-216**, 652 (2000).
[10] H.A.M. van den Berg. J. Appl. Phys. **60**, 1104 (1986).
[11] F. Magnus, R. Moubah, U.B. Arnalds, V. Kapaklis, A. Brunner, R. Schäfer, G. Andersson, B. Hjörvarsson. Phys. Rev. B **89**, 224420 (2014).
[12] E.N. Zubarev, V.N. Samofalov, A.Yu. Devizenko, I.Yu. Devizenko, V.V. Kondratenko, D.V. Sevryukov, V.A. Sevryukova, V.V. Mamon. J. Magn. Magn. Mater. **539**, 168301 (2021).
[13] A.G. Lesnik. Navedennaya magnitnaya anizotropiya v polikristallicheskikh plenkakh. Nauk. dumka, Kiev (1976). 163 s. (in Russian).
[14] S.D. Bader. Rev. Mod. Phys. **78**, 1, (2006).
[15] M.E. Stebliy, A.V. Ognev, A.S. Samardak, A.G. Kolesnikov, L.A. Chebotkevich, X. Han. J. Appl. Phys. **117**, 17A317 (2015).

Translated by Ego Translating