Modification of the “Transcritical” State in Ni$_{75}$Fe$_{16}$Cu$_{5}$Mo$_{4}$ Films Produced by RF Sputtering

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Received December 9, 2003

Abstract—The saturation magnetization, the perpendicular and rotational anisotropy constants, and the coercitivity of Ni$_{75}$Fe$_{16}$Cu$_{5}$Mo$_{4}$ thin magnetic films produced by rf sputtering are measured in the initial state and after annealing. A relation between the presence of perpendicular anisotropy and the “transcritical” state in the films is established. It is shown that, after additional thermal treatment, the magnetic softness of the films can be improved. © 2004 MAIK “Nauka/Interperiodica”.

INTRODUCTION

In recent years, the soft magnetic alloy Ni$_{75}$Fe$_{16}$Cu$_{5}$Mo$_{4}$ (so-called μ-metal) has once again attracted attention of researchers in connection with the possibility of using it in electronic devices based on the effect of giant magnetic impedance (GMI). The essence of the GMI effect lies in the variation of impedance $Z$ obtained from ac (at a frequency of $\omega$) measurements (i.e., the impedance of a conductor made of a soft magnetic ferromagnet and subjected to an external magnetic field): $Z(\omega) = R(\omega) - iX(\omega)$ [1, 2]. For such devices, the conductors are fabricated, as a rule, in the form of wires, tapes, foils, or film structures [3–5]. Today, the results of investigations of μ-metal samples in the form of foil [6] and films produced by magnetron sputtering [7] are available. These results show that these materials are suitable for GMI sensors. However, it should be noted that certain corrections accounting for the film state must be introduced and the properties of films can differ from those of a bulk sample made of the same material. The features of magnetic film production by sputtering can give rise to an induced perpendicular magnetic anisotropy in the samples. The emergence of such an anisotropy may be related to the columnar structure in the films, stresses existing in the films, the anisotropic distribution of atom pairs, etc. In each particular case, this anisotropy seems to be determined by the film material, as well as by the method and conditions under which the film is produced [8, 9]. The presence of the perpendicular anisotropy in a film, in its turn, can give rise to a “transcritical” state in it. This state is characterized by a specific hysteresis loop, enhanced coercitivity $H_c$, rotational magnetic in-plane anisotropy in the sample, and a fine strip domain structure when spontaneous magnetization in domains is oriented at an angle to the film surface [10, 11]. In this study, we investigate the “transcritical” state in Ni$_{75}$Fe$_{16}$Cu$_{5}$Mo$_{4}$ films produced by rf ion-plasma deposition.

EXPERIMENTAL

The films were deposited on water-cooled glass substrates in an argon atmosphere at a pressure of $1 \times 10^{-3}$ Torr. The fore vacuum was $5 \times 10^{-7}$ Torr. As a target, we used a plate 10 cm in diameter and made of Ni$_{75}$Fe$_{16}$Cu$_{5}$Mo$_{4}$ alloy. The composition of the deposited films was assumed to be the same as that of the target. The films were deposited in an external magnetic field parallel to the substrate surface to form anisotropy with an easy magnetization axis (EMA) in the plane of the sample. The magnitude of the field was about 100 Oe. The film thickness was measured by the Tolansky interference method. The hysteresis loops were measured by using the magnetooptical Kerr effect in a field range of ±100 Oe (the frequency of field variation was 50Hz) and by a vibrating-coil magnetometer in a field range of ±500 Oe. Saturation magnetization $M_s$ and the perpendicular anisotropy constant $K_p$ were determined by using a torquemeter according to the method described in [12]. The rotational anisotropy constant $K_\text{rot}$ was found from the torque curves (TC) measured in various fields from 10 to 500 Oe, with the field direction varying in the film plane. The domain structure was observed with the help of the powder figure method. The samples were annealed in vacuo under a pressure of $1 \times 10^{-6}$ Torr.
In this study, we present the results of investigation of two kinds of samples: 0.1 μm thick (sample 1) and 0.31 μm thick (sample 2). Figures 1a and 1b show the hysteresis loops measured by using a vibrating-coil magnetometer for samples 1 and 2 in the initial state, respectively. The field was applied parallel to the film surface. For the first (thin) film, a low-coercitivity rectangular loop typical of in-plane magnetized films is observed. The thicker sample has a loop typical of the films in the “transcritical” states. Such a state appears when the film thickness $L$ exceeds a certain critical value $L_c = 2\pi(A/K_p)^{1/2}$ and the $Q$ factor is $Q = K_p/2\pi M_s^2 < 1$, where $A$ is the exchange interaction parameter. Assuming that, for this alloy, $A = 2 \times 10^{-6}$ erg/cm [11] and using the values of the quantities $M_s$ and $K_p$ obtained for this sample (see table), we find that $L_c = 0.1$ μm. For the thin sample, a similar estimate gives $L_c = 0.1$ μm. Note that the values of $L_c$ are given within an accuracy of 0.1 μm and with allowance for the approximate nature of the used value of the exchange interaction parameter. Nevertheless, a comparison of the results of these estimates with the sample thickness makes it possible to assume that the probability of the second sample being in the transcritical state is higher than for the first sample.

One more argument in favor of this assumption is the observation of a microstripe domain structure in this sample (Fig. 2), which we failed to detect in the first film. It is the rearrangement of this domain structure during the magnetization reversal in the film that is responsible for the higher coercitivity and saturation field as compared to those for the first sample (see Fig. 1).

The third indication of the transcritical state in the thick sample is the presence of the rotational magnetic in-plane anisotropy in the film whose easy magnetization axis (EMA) is determined by the applied strong magnetic field. This field is capable of changing the strip domain orientation, which defines the position of the EMA. During the rotation of a weak magnetic field parallel to the film surface, the orientation of the strip domains remains unchanged, while the direction of magnetization in the domains is changed [10, 11]. Manifestations of the rotational anisotropy can be seen on the magnetooptical hysteresis loops and TCs.

Figure 3 shows schematically the magnetooptic hysteresis loops measured in the plane of sample 1 along (Fig. 3a) and perpendicularly to (Fig. 3b) the EMA. These loops are typical of the films characterized by in-plane anisotropy and in-plane magnetization. The same figure shows the magnetooptical hysteresis loop measured in the plane of sample 2 in any direction after a strong magnetic field ($\geq 100$ Oe) was applied in this direction. The field oriented in this direction the strip domains that determined the EMA position. However, if we rotate the sample (after the action of a strong field)