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Theoretical Interpretation of Positive Magnetoresistance in Permalloy Film

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Recently we reported the evolutionary transition from the positive magnetoresistance to the negative was discovered in the transverse configuration as the thickness of permalloy film increases. The discovered peculiarities of positive magnetoresistance phenomena were explained in the framework of the uniform rotation model of the film magnetization reversal.

1. Introduction

Recently we reported the evolutionary transition from the negative magnetoresistance (NMR) to the positive magnetoresistance (PMR) was discovered in the transverse configuration as the thickness of permalloy film increased [1]. Permalloy films have been investigated intensively because of their specific anisotropic magnetoresistance (AMR) suitable for their application in sensors and recording heads [2]. AMR, discovered by Thomson [3] in 1857, is manifested in the magnetoresistance (MR) dependence on the current direction with respect to the magnetization orientation. AMR is caused by differences in electron scattering when the electric current **I** is perpendicular or parallel to the magnetization orientation [2]. Usually, the longitudinal resistance increases with the magnetic field **H** where **H** and **I** are parallel, and the transverse resistance decreases where **H** and **I** are perpendicular to each other. The shape of the magnetic field dependence of MR (MR-H curve) is strongly varying in the low field range during the evolution of MR from longitudinal to transverse [4]. It is known that the low field magnetoresistance of ferromagnetic films depends on its magnetic domain structure. In particular, according to the recent experimental data [5], large MR effects due to domain walls are observed in magnetic films. At the same time, the domain structure and, correspondingly, magnetic properties of magnetic films can be strongly modified with the change of its thickness [6]. As a result, AMR must vary also. The understanding of interplay between transport and magnetic properties of magnetic films and also the study of possible modifications of MR-H curves are important to the fabrication of thin-film electronic devices.

We reported results on magnetoresistance and magnetometry measurements of permalloy films with varying thickness from 200 up to 2300 Å [1]. Here we approach the PMR phenomena in permalloy film with the theoretical interpretation. This will be useful to understand the influence of existing domain structure in magnetic films on its magnetic and transport properties and, in particular, on the variety of MR-H curves with the change of magnetic film thickness.

2. Experiment

The details of experimental procedure can be found in our previous work [1]. Briefly, by a DC magnetron sputtering system, $Ni_{80}Fe_{20}$ films were deposited on 1×1 cm^2 Si (100) substrates in a magnetic field of 300 Oe at the ambient temperature. The background pressure of the vacuum system was better than 5×10^{-7} Torr. The sputtering Ar pressure was 3 mTorr. The target to substrate spacing was 7.5 cm. The deposition rates of the samples ranged from 4 to 6 Å/s.

3. Results and Discussion

Fig. 1 shows hysteresis loops, obtained from VSM data for permalloy films with thickness $t = 1000$ Å and 1800 Å [1]. We can see a typical easy-axis hysteresis loop, characteristic for a single domain film, and so called a canted hysteresis loop for the sample with $t = 1000$ Å and 1800 Å, respectively. In both cases large Barkhausen jumps are observed for $H \cong \pm H_C$. The external part of the canted hysteresis loop ($|\mathbf{H}| > H_C$) is dominated by rotational mechanism. In the magnetic field perpendicular to the easy axis, the hysteresis curve of the first sample showed practically a linear variation of magnetization up to the saturation magnetic field, H_S as an evidence of the rotational mechanism of the magnetization reversal. The hysteresis loop of the second sample was unchanged. It is known [6, 7] that the

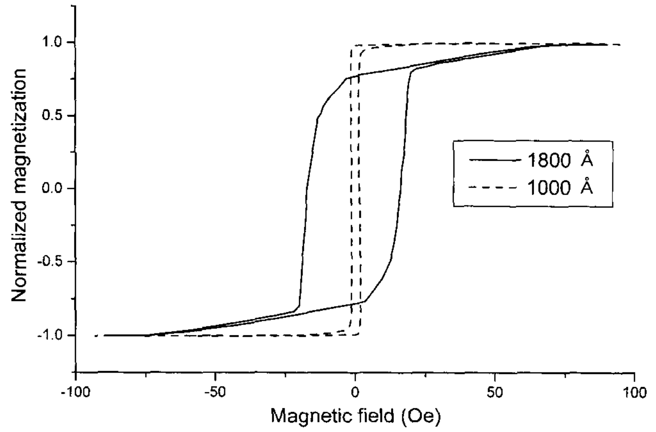

Fig. 1. The hysteresis loops of the permalloy films of 1000 and 1800 Å [1].

canted hysteresis loops exist in permalloy films with the stripe domain structure. The stripe domain structure is composed of many fine magnetic domains which have domain walls parallel to the previously applied field and whose magnetization directions point in one sense but deviate from the film plane upwards and downwards continuously. It was established that the easy and hard axis hysteresis loops (typical for thin samples) transformed to the canted hysteresis loop with the increase of the film thickness. The canted hysteresis loop showed considerably higher coercivity H_C than that of easy axis. The magnitude of H_C increased as the film thickness increased. The image of the magnetic force microscope (MFM) for the film of 1800 clearly confirmed the presence of stripe domains with the periodicity of 0.3 μm (see Fig. 2). The stripe domain structure can be explained by the perpendicular anisotropy [6, 7]. The reason of the perpendicular anisotropy was suggested the strain induced by the negative magnetostriction [7]. We can note that the complicated multi-domain structure was discovered for some thick films. The hysteresis loops of these samples were distinguished from the canted ones. According to the surface roughness measurement of 2 μm scan by atomic force micro-scope (AFM), the stripe domain structure film shows a higher surface roughness value (R_{rms} = 13.1 Å) than the multi-domain structure (R_{rms} = 7.7 Å) in the same thickness which was formed by a higher deposition rate, 6 Å/s. Higher deposition rate increased the critical thickness where the transition from NMR to PMR occurred as shown in Fig. 3 because the surface roughness decreased. Therefore, the surface roughness can cause the appearance of the stripe domain structure.

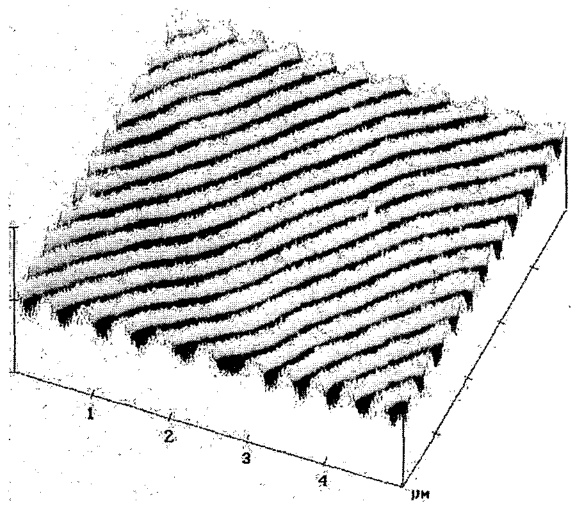

Fig. 2. The MFM image of the stripe domain structure in permalloy film.

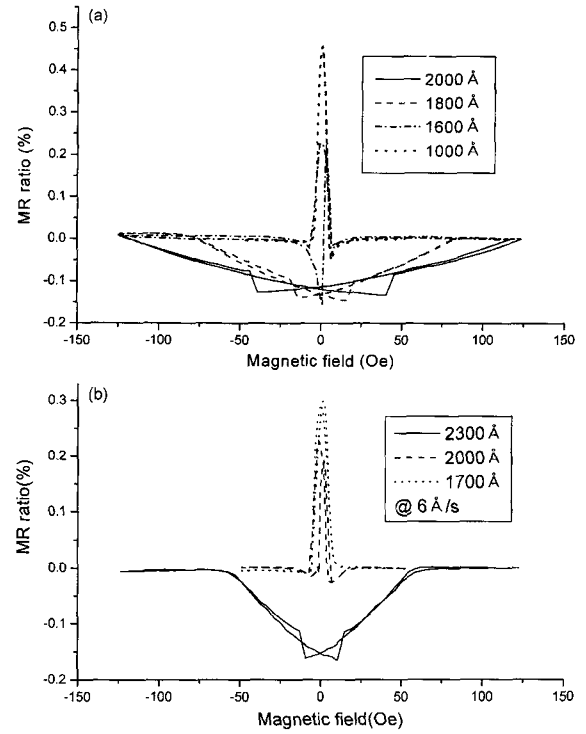

Fig. 3. The magnetic field dependencies of the MR ratio for the permalloy films with various thicknesses in the transverse ($\mathbf{H}\perp\mathbf{M} \parallel \mathbf{I}$) configuration with **H** scanning from the positive direction to the negative and back at the deposition rate of 4 Å/s (a) and 6 Å/s (b).

From the above, unanticipated magnetostrictive strain by the compositional fluctuation on deposition and/or the effect of surface roughness was suggested as a plausible mechanism of the perpendicular anisotropy. Fig. 4 shows typical MR-H curves, obtained for the permalloy films of 1000 Å and 1800 Å in the longitudinal ($\mathbf{H} \parallel \mathbf{M} \parallel \mathbf{I}$) and transverse ($\mathbf{H}\perp\mathbf{M} \parallel \mathbf{I}$) configurations with **H** scanning from the positive direction to the negative and back. In the first sample the applied magnetic field was parallel and perpendicular to the easy axis of magnetization. In the second the direction of **I** was parallel and perpendicular to stripe domain orientation. We can see that the MR-H curves in the transverse and longitudinal configurations are distinguishing. Moreover, the shape of MR-H curves in the transverse configuration is strongly modified as the film thickness increases. In particular, the MR-H curve of 1000 Å film has practically single positive peak for $H \cong 0$ (nega-

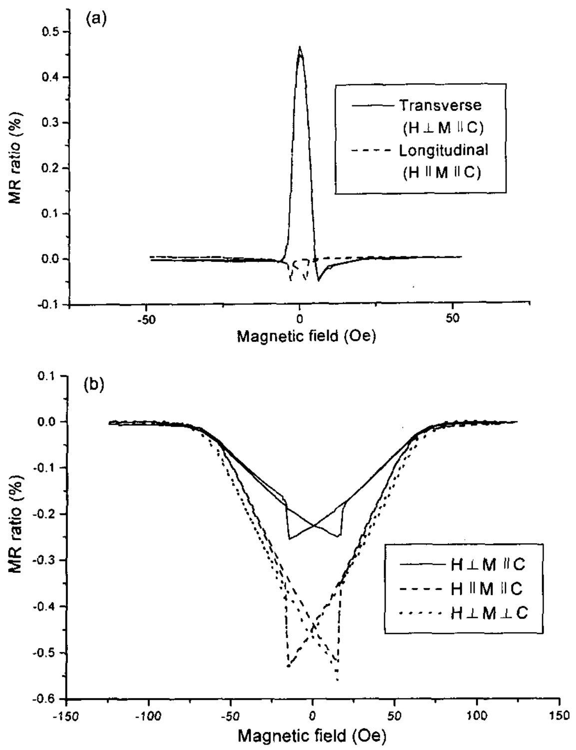

Fig. 4. The magnetic field dependencies of the MR ratio for the permalloy films of 1000 Å (a) and 1800 Å (b) in the longitudinal (**H** ॥ **M** ॥ **I**) and transverse (**H**⊥**M** ॥ **I**) configurations with **H** scanning from the positive direction to the negative and back [1].

tive magnetoresistance, NMR). The MR-H curve of the 1800 Å film (also as all MR-H curves in the longitudinal configuration) has the negative values (positive magnetoresistance, PMR) and shows an asymmetric and hysteretic cycle in the low field range. So, the transition from the NMR to PMR is observed in the transverse configuration with the increase of film thickness. The comparison of magnetic and transport properties of these sample showed that jumps of MR were observed for $H \cong \pm H_C$. The explanation of the received data can be as the following. It is known [2] that AMR is proportional to $\cos^2\varphi$, where φ is the angle between the magnetization **M** (H) and the electric current **I**. AMR curve can be hence linked to the magnetization rotation if this rotation is uniform. We have then $\mathbf{M}(H) = M_S\cos[\varphi(H)]$, where M_S is the saturation magnetization. For single domain film the magnetoresistance is determined by relation [2]:

$$\rho[\varphi(H)] = \rho_\perp \sin^2\varphi + \rho_\parallel \cos^2\varphi = \rho_\perp + (\rho_\parallel - \rho_\perp)\cos^2\varphi$$
$$= \rho_\parallel - (\rho_\parallel - \rho_\perp)\sin^2\varphi \quad (1)$$

The normalized quantity $\Delta\rho/\rho_{AV}$, where $\rho_{AV}=1/3\rho_\parallel + 2/3\rho_\perp$, is the anisotropic magnetoresistivity ratio. So, AMR ratio is proportional to the parallel magnetization component to the current, appearing during the magnetization reversal. For 1000 Å film the anisotropic magnetoresistance ratio is proportional to ($\cos^2\varphi$) and ($-\sin^2\varphi$) in the transverse and longitudinal configurations, respectively. In the transverse configuration AMR ratio is positive and has a maximum value for $H=0$ ($\varphi = 0°$). In the longitudinal configuration this sample has a practically rectangular magnetic hysteresis loop and, consequently, $\Delta\rho/\rho_{AV}$ must be distinct from zero only in the range of $H \cong \pm H_C$. Indeed, such magnetic field behaviour of $\Delta\rho/\rho_{AV}$ had been experimentally shown by us for the 1000 Å film. In the stripe domain structure film the external part of the canted hysteresis loop ($|\mathbf{H}| > H_C$) is dominated by rotational mechanism also. In this case the practically uniform rotation of the magnetization vectors takes place in every stripe domain. Consequently, both parallel and perpendicular to the stripe domain orientation in-plane magnetization components can exist, and the AMR ratio must be proportional $-\sin^2\varphi$ and $-\sin^2(\pi/2 - \varphi)$ in the longitudinal and transverse configuration, respectively. We can make the comparative estimations of the AMR ratio in the longitudinal and transverse configurations for the 1800 Å film with taking into account of these relations and the hysteresis characteristics of the sample. For example, while the magnetic field is changed from H_S to $H=0$, φ varies from 0 up to φ_1 where $\sin\varphi_1 = M_R/M_S \cong 0.8$ and from $\pi/2$ up to φ_1 where $\sin(\pi/2 - \varphi_1) = [1 - (M_n/M_S)^2 - \sin\varphi_1{}^2]^{1/2} \cong [0.36 - (M_n/M_S)^2]^{1/2}$ in the longitudinal and transverse configuration, respectively. Here M_n is the magnetization component perpendicular to the film plane and M_R/M_S is the normalized remanent magnetization. We can see that, indeed, for the considered sample the AMR ratio in the longitudinal configuration must be more than that in the transverse configuration (according to the above data, $(M_n/M_S) \neq 0$). If to suppose that $(M_n/M_S)^2 \cong 0.15$, we can obtain approximately triple difference between the longitudinal and transverse AMR ratios at $H = 0$ that was observed experimentally.

In the point of coercivity the uniform magnetization reversal is decomposed into a reversible magnetization rotation part and an irreversible jump of the magnetization. AMR ratio has also jumps (increases) in these points. This enlargement is proportional to $|(M_C/M_S)^2 - (M_R/M_S)^2|$ where M_C/M_S is the reduced magnetization at $H = H_C$. In the case that the magnetization reversal is not uniform, the magnetization **M** (H) and hence $\varphi(H)$ are defined by both wall displacements and the rotational mechanism. As a result, the AMR ratio can have a complicated dependence on H. In particular, the superposition of PMR and NMR is possible. The AMR measurements, performed on the films with complicated multi-domain structure, confirmed it. For illustration, Fig. 3 shows MR-H curves, received in the transverse configuration for permalloy films with varying thickness.

4. Conclusion

We have investigated the magnetic and anisotropic magnetoresistance properties of permalloy films with varying thickness. It was established that in the transverse configuration (**H⊥M || I**) the anisotropic magnetoresistance ratio changes from the negative to the positive with increasing the film thickness. The discovered peculiarities of the anisotropic magnetoresistance ratio were associated with the hysteresis characteristics of the studied samples and were explained in the framework of the rotational model of the magnetization reversal. It was found that in the case of the complicated multi-domain structure of films the superposition of the positive and negative AMR ratio was observed. As a result, the magnetic field dependence of AMR ratio has a complex shape.

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