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Domain structure and magnetization process of a giant magnetoimpedance geometry FeNi/Cu/FeNi(Cu)FeNi/Cu/FeNi sensitive element

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Abstract

The magnetization process and the magnetic domains of the FeNi (100 nm)/Cu (2.5 nm)/FeNi (100 nm)/Cu (480 nm)/FeNi (100 nm)/Cu (2.5 nm)/FeNi (100 nm) structure were studied. This geometry consists of two FeNi/Cu/FeNi trilayers with a thick in the direction perpendicular to the plane of the sensitive element and narrow in the direction of the flowing current Cu electrode in the centre. Ferromagnet/conductor/ferromagnet is the typical geometry of magnetoimpedance thin-film-based sensitive elements used to detect small magnetic fields. Multilayered structures were prepared by rf-sputtering in a magnetic field of 100 Oe applied perpendicular to the Cu electrode in order to induce transverse magnetic anisotropy. The magnetic measurements and magnetic domain structure observations were made in magnetic fields applied one at a time parallel or perpendicular to the Cu electrode. Different magnetization processes with non-homogeneous rotations in the first case and dominant multiple nucleation and merging of domains in the second one were observed.

1. Introduction

The magnetoimpedance effect, MI, is a subject of scientific and technological interest [1–5]. It shows up as a change in the high frequency complex impedance arising from field-induced modification of the dynamic permeability. It was shown recently that the MI effect

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which occurs in sandwiched soft magnetic film/non-magnetic conductor/soft magnetic film structures is stronger than that which occurs in a single-layered film of the same thickness [7–10]. The magnetoimpedance of the sensitive element in this geometry cannot be described analytically [7, 9, 10], which is a serious obstacle for design and applications. Some suggestions about the role of the domain structure have been proposed and special attempts have been made to undertake comparative studies of magnetoimpedance, magnetization processes and magnetic domains in many materials [10–12].

The magnetization process and magnetic structure of an MI sandwich is part of a topic of special interest: namely the effect of magnetic domains on thin films and the transport properties of multilayers [13, 14]. A general understanding of the field-dependent domain behaviour and the magnetization process of MI elements composed of soft magnetic film/narrow non-magnetic conductor/soft magnetic film may be very useful for the development of both theoretical models and functionality regimes, but this is not yet possible because of very limited experimental data.

In this work, the magnetic domains and magnetization process are studied in both easy and hard magnetization directions of an FeNi (100 nm)/Cu (2.5 nm)/FeNi (100 nm)/Cu (480 nm)/FeNi (100 nm)/Cu (2.5 nm)/FeNi (100 nm) structure in a magnetoimpedance element geometry, i.e. thick in the direction perpendicular to the plane of the sensitive element and narrow in the direction of the flowing current Cu electrode in the centre.

2. Experimental procedure, materials and methods

FeNi (100 nm)/Cu (2.5 nm)/FeNi (100 nm)/Cu (480 nm)/FeNi (100 nm)/Cu (2.5 nm)/FeNi (100 nm) structures with a thick narrow Cu electrode in the centre were prepared by rf-sputtering onto glass substrates using a $Ni_{81}Fe_{19}$ alloy target with a base vacuum of 10^{-6} and 10^{-3} Torr Ar pressure during deposition. The system was previously calibrated with respect to deposition rate of both FeNi and Cu thin films. Therefore the thickness of Permalloy and copper components was estimated by the deposition time at known deposition rate with experimental error less than 10% for thicknesses under consideration.

The magnetic field of 100 Oe was applied during the deposition procedure perpendicular to the longitudinal direction of the narrow Cu electrode in order to induce magnetic anisotropy in the magnetic layers (figure 1). The in-plane dimensions of each magnetic layer were 12 mm × 8 mm, and those of the Cu electrode were 9 mm × 1 mm, having two 1.5 mm × 1.5 mm Cu square contacts at each end (figure 1). The shape of the Cu electrode was determined by a mask during the deposition.

Very thin non-magnetic Cu layers were deposited without opening the vacuum chamber in a central part of each FeNi (100 nm)/Cu (2.5 nm)/FeNi (100 nm) trilayer. This was done to avoid the occurrence of a perpendicular magnetization component and a stripe domain structure formation. Perpendicular anisotropy may be caused by the structural anisotropy at high enough thickness as a result of a column structure formation [15, 16]. A magnetic field applied during the FeNi film deposition cannot block the column's growth but it can cause an in-plane induced anisotropy formation [16]. The presence of the perpendicular anisotropy component does not guarantee that the magnetization vector has an out-of-plane component. In order to answer the question about an effective anisotropy another important parameter such as the thickness of the film, L, must be taken into account. The critical thickness of the film, L_c, for the magnetization perpendicular component to appear can be estimated using the equation [17] $L_c = 2\pi (A/K_p)^{1/2}$, where K_p is the perpendicular anisotropy constant and A is the exchange interaction parameter. One may thus estimate the critical thickness of the

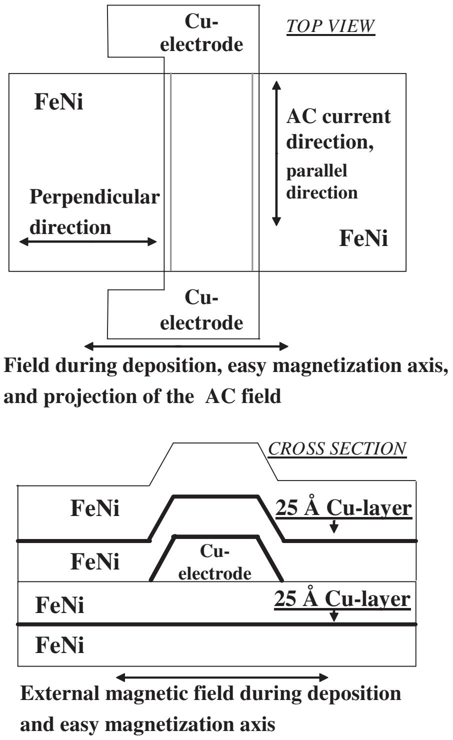


Figure 1. Principle diagram of the FeNi (100 nm)/Cu (2.5 nm)/FeNi (100 nm)/Cu (480 nm)/FeNi (100 nm)/Cu (2.5 nm)/FeNi (100 nm) magnetoimpedance sensitive element consisting of two FeNi/Cu/FeNi trilayers with a thick narrow Cu electrode in the centre.

$Ni_{81}Fe_{19}$ film for perpendicular anisotropy constant as follows [18]: $K_{\mathrm{p}} \sim 10^6$ erg cm^{-3} and $A = 2 \times 10^{-6}$ erg cm^{-1}, i.e. $L_{\mathrm{c}} \approx 100$ nm.

In order to avoid a stripe structure formation the thickness of the FeNi layers should not exceed the critical thickness of 100 nm for each layer. Furthermore, the thickness of the magnetic layer is an important parameter for MI-element functionality.

The value of the skin penetration depth, δ, was estimated using the equation [19] $\delta = [2\rho/(\omega\mu)]^{1/2}$ where ω is the alternating current angular frequency, μ is the effective magnetic permeability, and ρ is the resistivity of the Permalloy. For $\rho = 15\ \mu\Omega$ cm, $\mu = 1000$ and frequency of the alternating current of 50 MHz the skin penetration depth of about $\delta \sim 0.7\ \mu$m was obtained.

A strong skin effect appears when the skin depth reaches about half the thickness of the thin film. Therefore, very high frequencies are required for low thickness uniform thin films. But, in a multilayered soft magnetic film/non-magnetic conductor/soft magnetic film structure, a substantial change in impedance can occur at lower frequencies [7] compared with a single-layered soft magnetic film of the same composition. The general tendency is that a relatively high thickness of FeNi film is favourable for significant impedance variation at reasonably low frequency. Therefore, in order to increase the total thickness of the FeNi part of the MI element, but to avoid the appearance of perpendicular anisotropy, two FeNi (100 nm) layers separated by 2.5 nm Cu layer were deposited before and after the deposition of the narrow Cu electrode.

It is well known that FeNi-based MI sandwiches show rather modest values of the MI effect [7, 9] compared with Co-based structures [8]. At the same time, the technology of the non-multilayered Permalloy film preparation is well known and existing knowledge about their magnetic anisotropy, magnetic properties and domains [12] provide a solid basis for investigation of complicated structures with FeNi components of different thicknesses.

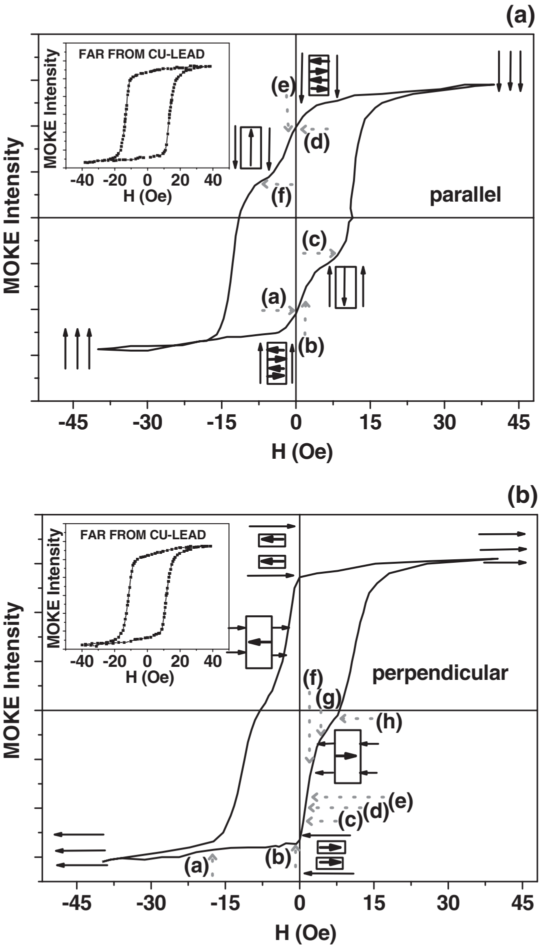


Figure 2. Magneto-optical $M(H)$ loops taken from the top FeNi layer (see figure 1) of the magnetoimpedance sensitive element, consisting of two FeNi/Cu/FeNi trilayers with a thick narrow Cu electrode in the centre. The external fields were applied parallel (a) and perpendicular (b) to the Cu electrode. The light spot was covering the part of the trilayer on top of the thick conducting Cu electrode and adjacent area. Insets show $M(H)$ loops taken from the top FeNi layer of the FeNi/Cu/FeNi/FeNi/Cu/FeNi multilayer further from the Cu electrode. Schematic drawings are a qualitative explanation of the shape of the $M(H)$ loop. Grey arrays show external fields for the magnetic domain observation (see also figure 3 for the parallel and figure 4 for the perpendicular case).

The surface magnetization was obtained by the transverse magneto-optical Kerr effect, MOKE. The light was linearly polarized in the plane of incidence which is perpendicular to the applied magnetic field. The radiation was directed to the sample at an angle of incidence of 65°. The spot size was about 5 mm. During the experiment neither the angle of incidence nor other parameters that could affect the data collection were changed. The $M(H)$ loops were measured in a magnetic field up to 40 Oe.

The spot focused first in the zone corresponding to the centre of the Cu electrode, which included a region of the upper trilayer on top of the thick conducting Cu electrode and adjacent regions deposited directly on the lower trilayer. The $M(H)$ loops in this case show the remagnetization of both regions (figure 2). To distinguish each contribution, two loops were measured far from the Cu electrode. One was measured in the field parallel to the direction of the Cu-electrode long side, denoted as the parallel direction. The other was measured in the perpendicular direction in the plane of the film, designated as the perpendicular direction (figure 1). The domain structure was studied by the longitudinal Kerr effect [12, 20] for the 45° orientation of the incidence plane and in a magnetic field up to 40 Oe in both the easy magnetization direction (perpendicular to the long side of the Cu electrode) and the hard magnetization direction (parallel to the Cu electrode).

The MI value was measured in a magnetic field applied parallel to the Cu electrode, being of the order of 2–4% for 50 MHz frequency. No magnetoimpedance effect for the available accuracy was observed in a magnetic field applied perpendicular to the Cu electrode. Details of the MI measurements can be found elsewhere [9].

3. Results and discussion

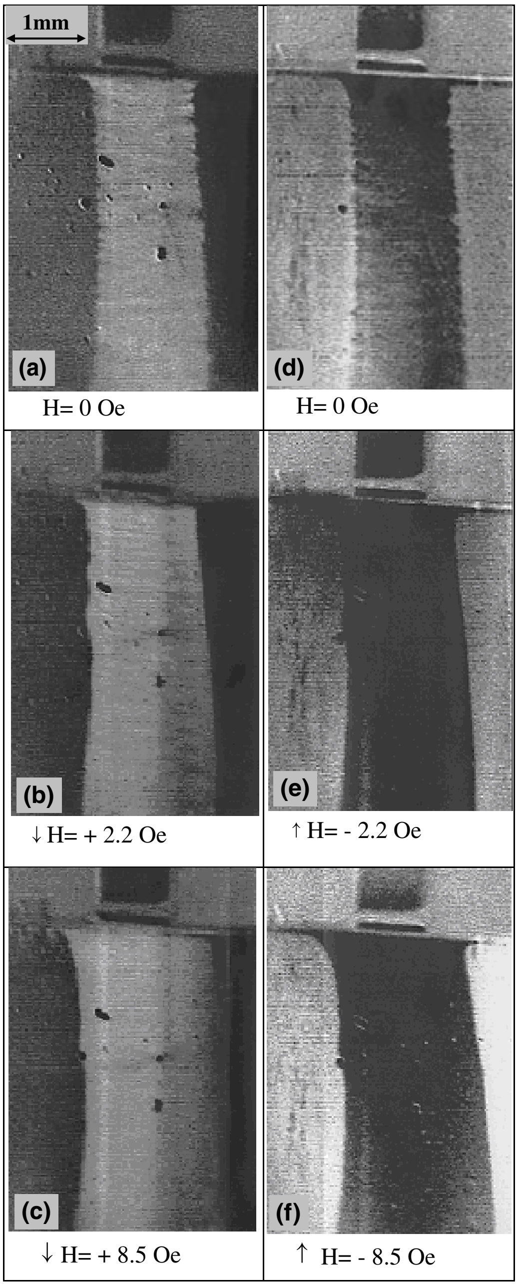
An analysis of the shape of the $M(H)$ loops (insets in figure 2) shows that far from the Cu electrode the FeNi (100 nm)/Cu (2.5 nm)/FeNi (100 nm) multilayer remagnetizes as a whole structure in both the parallel and perpendicular directions. In the perpendicular direction, i.e. in the direction of the external magnetic field applied during the sensitive element deposition, lower coercivity of about 11.5 Oe was obtained, compared with a coercivity of 13.5 Oe in the direction parallel to the Cu electrode. The $M(H)$ loops measured for the trilayer on top of the thick conductive Cu electrode shows the same tendency: the perpendicular direction (figure 2) is the easy magnetization direction.

The magnetization process in the parallel direction, starting from a saturated state in the negative field, can be described as follows. The MOKE signal intensity for measurement of the FeNi/Cu/FeNi trilayer on top of the Cu electrode shows a small decay up to the field of about 2 Oe compared with the signal in the saturated state. The first fast magnetization decay starts in small negative field close to zero. The beginning of the second decay corresponds to a field of about 8 Oe, i.e. we can observe a two-step $M(H)$ loop. The $M(H)$ loop measured far from the Cu electrode is a one-step loop as described above.

The two-step shape of the $M(H)$ loop taken near the Cu electrode indicates the existence of two different contributions to the magnetization process. The FeNi/Cu/FeNi trilayers on top and below the Cu electrode have lower coercivity and therefore the first $M(H)$ decay near zero field corresponds to remagnetization of the zone near the Cu electrode. In a higher field, about 11 Oe, away from the Cu electrode, the FeNi/Cu/FeNi/FeNi/Cu/FeNi multilayer remagnetizes and the second step of $M(H)$ decay appears.

The magnetization process in the field applied in the perpendicular direction is similar to that in the parallel direction. The external field decrease starting from negative saturation up to zero field results in a small decrease of the MOKE signal for measurement of the FeNi/Cu/FeNi trilayer on top of the Cu electrode compared with a signal in the saturated state. In a small positive field close to zero the first fast magnetization decay starts. This behaviour could be explained as a consequence of the remagnetization of FeNi/Cu/FeNi trilayers on the top and bottom of the Cu electrode. The beginning of the second decay resulting from the remagnetization of the FeNi/Cu/FeNi/FeNi/Cu/FeNi multilayer further from the Cu electrode appears in the field of about 8.5 Oe. The schematic drawings in figure 2 were not retrieved from the Kerr measurements. They offer a schematic explanation of the shape of the $M(H)$ loop together with the domains observed in the external fields (see figures 3 and 4). Black arrays show the suggested position of the projection of the magnetization on the plane of the film in different zones.

Figure 3 displays the magnetic domains in the selected states for the field applied parallel to the Cu electrode. The images were taken near the edge, but the structure is the same over the length of the Cu electrode. The two FeNi/Cu/FeNi trilayers with a thick narrow Cu electrode in the centre element were first saturated in a high negative field of −40 Oe. No magnetic structure was observed in the negative field of −40 Oe. After the negative saturation, a wide pattern appears in zero field in the trilayer on top of the Cu electrode and in a narrow adjacent area as was suggested on the basis of the analysis of the $M(H)$ loop. There is a variation of the light intensity in different zones of the image of this wide pattern.



H= 0 Oe

H= 0 Oe

↓ H= + 2.2 Oe

↑ H= - 2.2 Oe

↓ H= + 8.5 Oe

↑ H= - 8.5 Oe

Figure 3. Magnetic domain changes in the sensitive element, consisting of two FeNi/Cu/FeNi trilayers with a thick in the direction perpendicular to the plane of the sensitive element and narrow in the direction of the flowing current Cu electrode in the centre, for the external field applied parallel to the Cu electrode (see figure 1).

It is assumed, therefore, that it has a fine magnetic structure with the magnetization vector projections oriented in the perpendicular direction (see figure 2(a)). Increasing the magnetic field up to 7.5 Oe (figures 3(b) and (c)) results in a slight extension of the wide pattern to the narrow successive area close to the Cu electrode. But the variation of light intensity, which indicates the presence of the magnetic structure in different zones of the image of the wide pattern, disappears as a consequence of the non-homogeneous magnetization rotation towards the parallel direction. The subsequent increase of the external field leads to extension of the

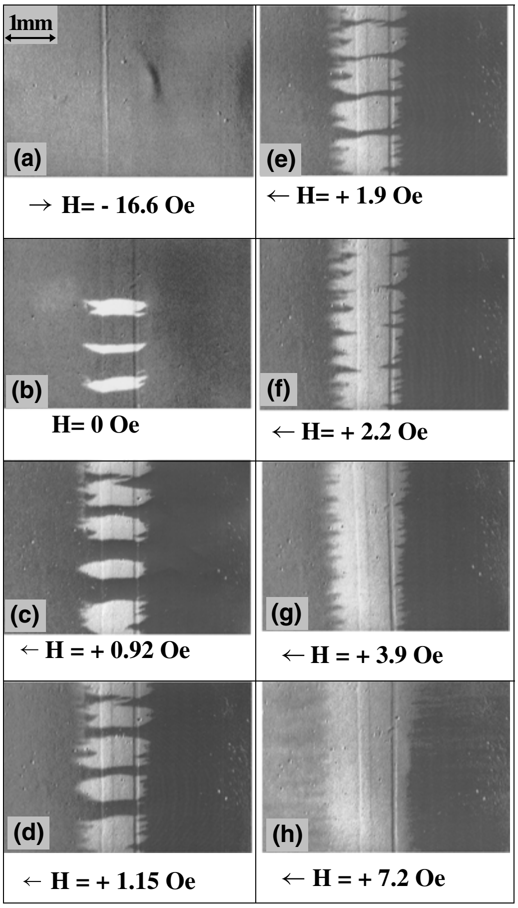


Figure 4. Magnetic domain changes in the sensitive element, consisting of two FeNi/Cu/FeNi trilayers with a thick in the direction perpendicular to the plane of the sensitive element and narrow in the direction of the flowing current Cu electrode in the centre, for the external field applied perpendicular to the Cu electrode (see figure 1).

central wide pattern into the FeNi/Cu/FeNi/FeNi/Cu/FeNi trilayer far from Cu-electrode part of the element in accordance with the second MOKE signal decay (figure 2(a)).

Figure 4 shows the magnetic domains for the external field applied in the perpendicular direction after the application of −40 Oe field. There is no domain structure visible on the level of optical resolution in any interval from −40 Oe to almost zero field (figure 4(a)). In a small negative field, very close to zero, two or three wedge domains appear (figure 4(b)). They are situated at fixed distances from each other, determined most probably by their magnetostatic interaction.

One may suggest that the magnetization vectors in all wedge domains are parallel to the perpendicular direction, which is also the easy magnetization direction (see figure 2(b)). One of the arguments supporting this point of view is that the zigzag shape of the domain wall between the wedge and the main volume looks like a typical charged zigzag wall and seems to be separating two domains meeting head-on [12].

An increase in the external field leads to an increase of the number of wedge domains, i.e. multiple nucleation processes, and the growth of the relative volume of a single wedge (figure 4(e)). Increasing the external field up to +2.2 Oe results in a merging of all wedges in a brush-like structure (figures 4(f) and (g)). A subsequent increase of the external field results in the brush-like structure extending to the FeNi/Cu/FeNi/FeNi/Cu/FeNi part of the element which is further from the Cu electrode in accordance with the second MOKE signal jump (figures 4(h) and 2(b)). The spread of the brush-like structure seems to appear as a magnetization reversal in the field close to +7.2 Oe and propagation of the domain walls. This process is visible through a microscope. Similar processes to those mentioned above take place for the field changes from the positive saturation in a field of +40 Oe to the −40 Oe field.

4. Conclusions

The magnetization process and magnetic domains of a magnetoimpedance element consisting of two FeNi/Cu/FeNi trilayers with a thick narrow Cu electrode in the centre were comparatively analysed. The two FeNi/Cu/FeNi trilayers on top of and below the Cu electrode show lower coercivity both in the field applied parallel and in that applied perpendicular to the Cu electrode than theFeNi/Cu/FeNi/FeNi/Cu/FeNi part further from the Cu electrode. In a small field up to 2.2 Oe, the domain structure evolution consisted of dominant multiple nucleation sites and merging of the wedge domains for the field perpendicular to the Cu electrode and of non-homogeneous rotations for the parallel field.

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