Analysis of steplike change of impedance for thin-film giant magnetoimpedance element with inclined stripe magnetic domain based on magnetic energy

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(Presented on 10 January 2007; received 31 October 2006; accepted 11 December 2006; published online 1 May 2007)

The phenomenon of steplike impedance change for thin-film giant magnetoimpedance (GMI) element was reported. The steplike change happens simultaneously with the appearance or the disappearance of stripe magnetic domain. This phenomenon is obtained for amorphous $Co_{85}Nb_{12}Zr_3$ soft magnetic thin film in a rectangle shape with an in-plane uniaxial easy axis in the direction nearly 60° against the short-side axis of the element. The steplike change of impedance appears in a certain magnitude of external magnetic field. A high-sensitive magnetic field sensor can be realized by applying this phenomenon. In this study, a mechanism of the appearance or the disappearance of inclined stripe magnetic domain is discussed based on an analysis of magnetic domain energy, for the purpose of applying to a high-sensitivity magnetic field sensor. We assume these extremely different magnetic domains as (I) stripe domain with closure domain and (II) single domain, based on experimentally observed domain structures. The result of analysis shows that the magnetic energy of these two phases intersects each other in a certain external magnetic field, which means that the basis of steplike GMI of thin-film element is revealed as a structural change of magnetic domain based on magnetic energy.
[DOI: 10.1063/1.2711073]

INTRODUCTION

The giant magnetoimpedance (GMI) phenomenon is well known as an effect of a significant change in impedance of the element, when it is placed in a magnetic field. The GMI effect is caused by a change of permeability induced by applying an external magnetic field. The dominant direction of the permeability which changes the element impedance is the direction of the alternating magnetic field induced by a high-frequency current conducting in the element. The change of permeability with applying the external magnetic field is caused by an interaction of the external magnetic field with both a magnetic anisotropy and a magnetic domain structure of the element.

The GMI element with the property of steplike impedance change was reported.[1,2] It is obtained for amorphous $Co_{85}Nb_{12}Zr_3$ soft magnetic thin film in a rectangle shape with an in-plane uniaxial easy axis in the direction of nearly 60° against the short-side axis of the element.[1] The steplike change of impedance happens simultaneously with the appearance or the disappearance of stripe magnetic domain.[2] The relationship of the impedance with the domain structure was discussed based on both the bias-susceptibility model of a magnetic thin film with uniaxial anisotropy[2] and experimentally observed the change of the stripe domain pattern with applying external magnetic field.[3] This theoretical model qualitatively explains the steplike change of impedance in the case of the appearance or the disappearance of stripe domain. But a physical basis of the change of magnetic domain is not clear yet.

In this study, a mechanism of the appearance or the disappearance of inclined stripe domain is discussed based on an analysis of magnetic domain energy. It is assumed that these extremely different domain structures are as follows: the stripe domain consists of contiguous antiparallel domains with closure domains, and the domain after disappearance of the stripe consists of a single domain. This assumption is based on experimentally observed domain structures. It is shown, as a result of this paper, that the energy of these extremely different domain structures intersects each other in a certain external magnetic field in a certain range of in-plane angle of the easy axis direction.

SIMULATION MODEL

Two simulation models for estimating the magnetic energy is discussed in this section. At first experimentally obtained change of magnetic domain is shown as a basis of our

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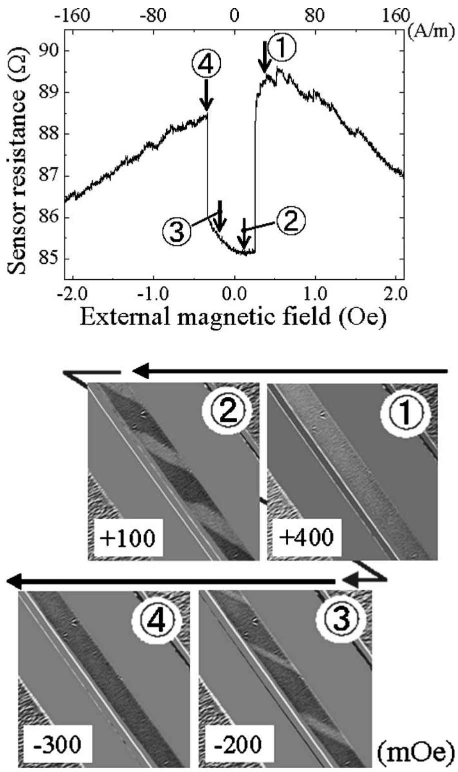

FIG. 1. Relationship between the domain structure and the impedance step. (a) Variation of impedance and (b) variation of domain structure.

simulation model. Figure 1 shows a variation of inclined stripe domain as a function of external magnetic field. Figure 1 also shows a variation of the element impedance in the case of 50 MHz. The domains in match with the impedance are shown by caption numbers. The steplike impedance phenomenon is characterized as follows: the inclined stripe domain appears or disappears simultaneously with the steplike impedance phenomenon in a certain magnetic field. The width of stripes changes as a function of external field in the range of magnetic field where the stripe domain is observed. The domains which have a magnetic momentum in the direction of nearly parallel to the external field extend the width of domains, and the domains with nearly antiparallel momentum narrow. This change of magnetic domain is executed with conserving the direction of domain wall. The directions of domain walls are almost in the direction of easy axis.

Figure 2 shows models of magnetic domains which are applied to our simulation. Figure 2(a) shows a model of domain in the case of stripe domain called as model I. An existence of closure domains is assumed in model I. Figure 2(b) shows a model of domain in the case of single domain called as model II. These models are two-dimensional models with infinite length; therefore it means a neglect of longitudinal demagnetizing energy.

The magnetic energy of model I is obtained by Zeeman energy, anisotropy energy, and wall energy. The magnetostriction of amorphous $Co_{85}Nb_{12}Zr_3$ thin film is small enough to be negligible. The magnetic charge on the wall of closure domain is assumed to be neglected in this simulation. In this model, the anisotropy is uniaxial. The wall energy γ is estimated by

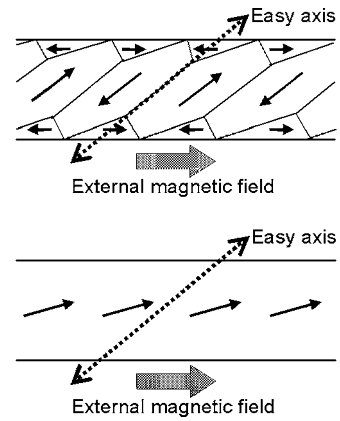

FIG. 2. Simulation model of the magnetic domain. (a) Model for the stripe domain and (b) model for the single domain.

$$\gamma = 2\sqrt{A}\,\sin\xi\int_0^{\pi}\sqrt{g(\xi,\varphi)}d\varphi \quad (\mathrm{J/m^2}), \tag{1}$$

where A is the exchange stiffness constant, assumed to be $A = 1.49\times 10^{-11}$ J/m in this simulation, and g is the anisotropy energy. The integral of the equation means an integration of anisotropy energy of the domain wall. The parameter φ is the azimuthal angle of magnetic momentum based on the normal axis of the wall plane, and θ is the angle of momentum against the normal axis.

In the case of 180° wall, the wall energy γ_{180} is obtained as follows:[4]

$$\gamma_{180} = 2\sqrt{A}\int_0^{\pi}\sqrt{K_u\sin^2\varphi}\,d\varphi = 4\sqrt{AK_u} \quad (\mathrm{J/m^2}), \tag{2}$$

where K_u is the uniaxial anisotropy constant. In this simulation K_u is 260 $\mathrm{J/m^3}$ and M_s is 0.93 T.

In the case of closure domain wall, the wall energy γ_c is obtained as follows:[4]

$$\gamma_c = 2\sqrt{A}\,\sin\xi\int_0^{\pi}\sqrt{g(\xi,\varphi)}d\varphi \quad (\mathrm{J/m^2}),$$

$$\text{where}\quad g(\xi,\varphi) = K_u\{1-[1-\sin^2\xi(1-\cos\varphi)]^2\}. \tag{3}$$

In the case of model I, the movement of domain walls is restricted as the observation in Fig. 1, when the external magnetic field changes. It means that they move with conserving the direction of 180° wall in the direction of the easy axis.

Model I consists of a Landau-Lifshitz-like configuration with closure domains at the edge.[5] It also resembles to the well-known sectional domain structure of stripe domain for perpendicular anisotropy thin film.[6,7] But our target is the in-plane domain structure for in-plane anisotropy thin film with quite different dimensions, 20 μm of width.

In the case of model II, the magnetic energy is obtained by Zeeman energy, magnetic static energy, and anisotropy energy. In this case, the direction of magnetic momentum is obtained as almost longitudinal. Our analysis shows that it is the direction of minimum energy, because of an effect of demagnetizing energy along the width direction. The demag-

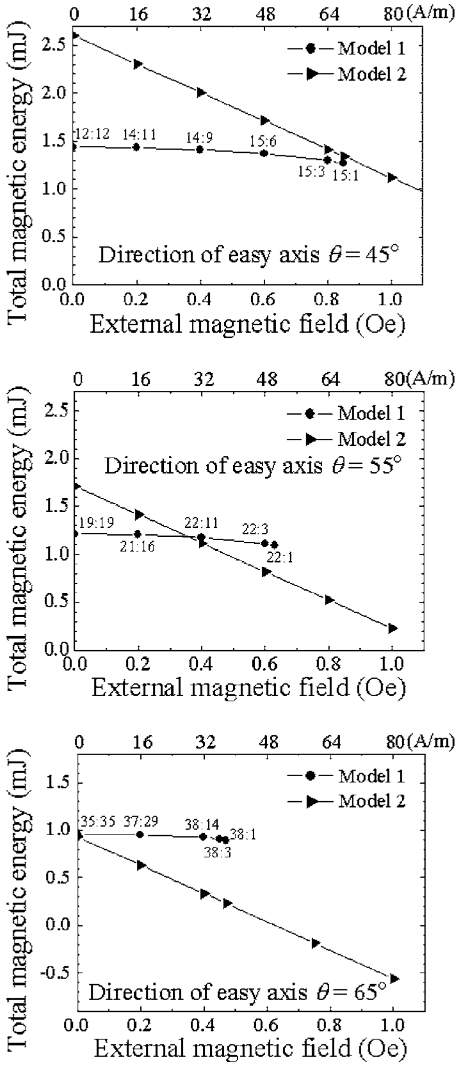

FIG. 3. Relationship between external magnetic field and total magnetic energy.

netizing energy is calculated only in the direction of width, because there is no demagnetizing field in the length direction with its infinite length.

SIMULATION RESULTS AND DISCUSSION

Figure 3 shows a result of simulation. This figure shows a relationship between external magnetic field and total magnetic energy. The relation for the stripe domain is plotted by solid circles, and the relation for the single domain is plotted by solid triangles. The directions of uniaxial easy axis against the short-side axis θ are (a) 45°, (b) 55°, and (c) 65°. Ratios of domain width for nearly parallel and nearly antiparallel are indicated besides the plots. From these results, if the domain state is assumed to keep lower energy, three cases of transition are predicted. In the case of (a), the stripe domain gradually disappears as increasing the external magnetic field, and then smoothly connected to the single domain. In the case of (b), the stripe domain transforms to the single domain in spite of existing a certain width of antiparallel magnetic domain. In the case of (c), only the state of single domain exists. The previously reported experimental results show that the direction of easy axis in which the steplike phenomenon was observed was ranging from 55° to 75°.[1] On the other hand the range predicted by this simulation is ranging from 45° to 65°. This difference is assumed to be caused by a demagnetizing energy based on a longitudinal demagnetizing field in model II. The experimental results were obtained by three-dimensional elements with the length ranging from 1000 to 3000 μm and the thickness from 2 to 4 μm, whereas the simulation model has an infinite length. The finite length brings an increment of magnetic energy for model II, but there is slight difference for model I. If the longitudinal demagnetizing energy is taken into consideration, the simulated range of easy axis would be brought near to the experimental results.

SUMMARY

A mechanism of the appearance or the disappearance of inclined stripe magnetic domain for steplike GMI phenomenon is discussed based on an analysis of magnetic domain energy. We assume these extremely different magnetic domains as (I) stripe domain with closure domain and (II) single domain, based on experimentally observed domain structures. The result of analysis shows that the magnetic energy of these two phases intersects each other in a certain external magnetic field and in a certain direction of uniaxial easy axis, which is in the value near to the experimentally obtained. This means that the basis of steplike GMI of thin-film element is revealed as a structural change of magnetic domain based on magnetic energy.

We can propose a high-sensitivity magnetic field sensor by applying this steplike phenomenon, such as based on impedance-step detection, conventional magnetoimpedance detection, and so on. The physical basis of the steplike phenomenon declared by this study gives important information for improving sensitivity for these magnetic field sensors.

ACKNOWLEDGMENTS

This work has been supported by Nationwide Cooperative Research Projects by Research Institute of Electrical Communication, Tohoku University.

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