ANALYSIS OF STABLE DOMAIN STRUCTURE IN MAIN-POLE FILM
FOR PERPENDICULAR MAGNETIC RECORDING HEAD

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The Domain structure in a main-pole film is analyzed by calculating energies to obtain a stable and highly efficient SPT head. Assuming a closure domain structure, the sums of anisotropic energy and wall energy are calculated. It is considered that the domain structure is unstable when the domains with different number have the same energy. Output efficiency η is estimated from an effective width of a 180° wall where a magnetic flux flows. It is found that the domain structure changes easily and the change in η is appreciable as the anisotropic constant K_u decreases. As the track width narrows, low K_u instability becomes frequent. It is necessary for K_u to be precisely controlled in main pole film with a small aspect ratio so that the domain structure shows almost no change under a low K_u . By doing this, a highly efficient head with a narrow track width is obtained.

INTRODUCTION

A narrow track head has been studied to increase the surface recording density in a perpendicular magnetic recording. As the track width narrowed, the reproduced voltage was found decrease and unstable[1]. Nakamura, et al. observed the domain structure of the main-pole film by the Bitter method and ascertained the instability of the domain structure in the narrow track. It has also been found that a head with a low aspect ratio drives more stably[2]. Moreover, when the anisotropic constant K_u is small, the reproduced voltage decreases. However, the mechanism of this instability has not been clarified for unstable domain structure and the unstable reproduced voltage. In this paper, the stability of the domain structure and output efficiency are investigated by calculating the energies of the domain structure.

METHOD OF CALCULATION

2.1 Analytical model

The domain structure of the main-pole film is assumed to be of the closure type shown in Fig.1. It consists of triangular domains, quadrangular domains and hexagonal domains. Assumptions for the numerical analysis were made as follows:

- (1) The domain structure does not vary perpendicular to the film plane.
- (2) The magnetization $\mathbf{M}$ is uniform within each domain, and is consistently parallel to the film plane.
- (3) Walls between domains are approximated by straight lines.

Wall positions and magnetization directions without an applied field are determined so that the magnetostatic energy is zero[3]. Namely, triangular domains are set as right triangles, and the magnetizations are parallel to the film side surfaces and the 180° walls. Anisotropic energy and wall energy are calculated based on the above assumptions.

The unit domain is defined to consist of two triangular regions and two quadrilateral regions, as shown in this figure.

Fig.1 Typical domain structure of magnetic thin film used for analysis.

2.2 Energies of the domain structure

2.2.1 Anisotropic energy

The anisotropic energy E_a is expressed as

$$E_a = K_u \sum_{i=1}^{n_d} (\sin \theta_i) \Omega_i d, \quad (1)$$

where K_u is an anisotropic constant, θ_i is the angle between the magnetization direction and the easy axis, Ω_i is the area of each domain, d is film thickness, and n_d is the total number of domains.

2.2.2 Wall energy

The wall is assumed to consist of a Bloch-type component and a remaining component which behaves like a Néel-type wall [4]. The Bloch-type wall energy e_{wb0} and the Néel-type wall energy e_{wn0} is expressed as [5]

$$e_{wb0} = \sigma_{b0} \sin^2(\theta_w/2), \quad (2)$$

and

$$e_{wn0} = \sigma_{n0} \{1 - \cos(\theta_w/2)\}^2, \quad (3)$$

where σ_{b0} is energy per unit area of a 180° Bloch-type wall for an anisotropic constant K_{u0} , σ_{n0} is energy per unit area of a 180° Néel-type wall for K_{u0} , and θ_w is the rotation angle of $\mathbf{M}$. The wall energy e_{w0} is expressed as [4]

$$e_{w0} = \left\{ \left(\frac{\mathbf{M}_b}{\mathbf{M}} \right)^2 e_{wb0} + \left(\frac{\mathbf{M}_n}{\mathbf{M}} \right)^2 e_{wn0} \right\} \gamma d, \quad (4)$$

where $\mathbf{M}_b$ and $\mathbf{M}_n$ are the Bloch-type component and the Néel-type component of $\mathbf{M}$, respectively, γ is the wall length, and d is the film thickness. The sum of the components $\mathbf{M}_b$ and $\mathbf{M}_n$ is equal to $\mathbf{M}$ and the ratio of $\mathbf{M}_b$ to $\mathbf{M}_n$ is determined so that e_{wn0} is minimized.

Total wall energy of the domain structure is expressed as

$$E_{w0} = \sum_{j=1}^{n_w} e_{wj} \quad (5)$$

where n_w is the total number of domain walls.

The wall energy E_w at any K_u is assumed to be represented as follows.

$$E_w = (K_u/K_{u0})^n \cdot E_{w0} \quad (n \geq 0). \quad (6)$$

The wall energy constants σ_{b0} and σ_{n0} , and the multiplier n are determined so that the K_u dependence of the number of unit domains N corresponds with the experimental results as shown in Fig.2(a), (b) and (c). The experimental results are indicated by the open circles in these figures, for a long $50 \mu\text{m}$ -wide and $0.3 \mu\text{m}$ -thick amorphous CoZrNb alloy, with a magnetization saturation M_s of about 10^6 A/m [1]. The number of unit domains per $40\text{-}\mu\text{m}$ length is examined.

The calculation results are indicated by the filled circles, for the $50\text{-}\mu\text{m}$ -wide, $40\text{-}\mu\text{m}$ -long, and $0.3\text{-}\mu\text{m}$ -thick film, with M_s of 10^6 A/m , and K_{u0} of 340 J/m^3 . The energy of the domain structure is calculated as a function of the number of unit domains, and the number with the lowest energy is indicated in these figures.

First of all, n is determined so that the ratio of the change in N corresponds to that obtained from the experimental results, and σ_{b0} is decided so that N corresponds to that obtained from the experimental results. Since σ_{n0} can not be determined experimentally as shown later, the previous calculation result is used.

The n dependence on the change in N is indicated in Fig.2(a), where σ_{b0} is $1.0 \times 10^{-3} \text{ J/m}^2$ and σ_{n0} is 1.0×10^{-2}

(a) Multiplier n dependence.

(b) Bloch wall energy constant σ_b dependence.

(c) Néel wall energy constant σ_n dependence.

Fig.2 Determination of wall energy parameters corresponding to the experimental results.

J/m^2 . When n is $1/2$, N increases from 2 to 3 as K_u changes from 100 to 700 J/m^2 . When n is 0, N changes from 1 to 4. The ratio of the change in N agrees more closely to the experimental result for the small n . It seems that the wall energy does not change even if K_u changes. Therefore, n is assumed to be 0 in this analysis.

The dependence of σ_{b0} is indicated in Fig.2(b). Here, σ_{n0} is set at $1.0 \times 10^{-2} \text{ J/m}^2$, which is the previous calculated value[5]. As σ_{b0} becomes small, N increases. These results show that an appropriate value for σ_{b0} is $1.0 \times 10^{-3} \text{ J/m}^2$.

The dependence of σ_{n0} is shown in Fig.2(c), with $n=0$ and $\sigma_{b0}=1.0 \times 10^{-3} \text{ J/m}^2$. The number of domains N is large for a small σ_{n0} . However, N does not change even if σ_{n0} is varied as 1.0×10^{-2} , 10.0×10^{-2} , and $100.0 \times 10^{-2} \text{ J/m}^2$. Therefore, σ_{n0} cannot be determined by comparison with the experimental results. Middelhoek calculated σ_{n0} as $1.0 \times 10^{-2} \text{ J/m}^2$, for the $0.3 \mu\text{m}$ -thick film, with $M_s=10^6 \text{ A/m}$ and $K_u=340 \text{ J/m}^3$ [5]. In this analysis, the wall energy parameters are decided as follows: $\sigma_{b0}=1.0 \times 10^{-3} \text{ J/m}^2$, $\sigma_{n0}=1.0 \times 10^{-2} \text{ J/m}^2$, and $n=0$.

2.2.3 Estimation of output efficiency

The output efficiency η for the main-pole film with the closure domain structure is estimated as,

$$\eta = (w \cdot d) / (K_u \cdot L), \quad (7)$$

where w is the width of the 180° wall, d is the thickness, and L is the length, as shown in Fig.1. The output efficiency is proportional to the cross sectional area ($w \cdot d$), because the magnetic flux flows mainly through the tetragonal and hexagonal regions, by the magnetization rotation. As the permeability is in inverse proportion to K_u , output efficiency is also assumed to be in inverse proportion to K_u .

Results and Discussion

3.1 Aspect ratio of film with stable domain structure

Energy is calculated as a function of the aspect ratio L/t of the film, as shown in Fig. 3. The track width t is fixed at $50\text{ }\mu\text{m}$, the film thickness d is fixed at $0.3\text{ }\mu\text{m}$, and the length L is varied. The K_u is 110 J/m^3 . The filled circles show the energy when N is 1, and the open circles show the energy when N is 2. The energy with $N=1$ is almost the same as the energy with $N=2$, when L/t is about 0.8. Thus, N is thought to be change easily between 1 and 2, and the domain structure to be unstable. As L/t becomes small, the energy increases. In this region, the domain structure seems to change easily into a quasi-stable condition. For example, an extra wall may appear in the middle of a domain[6]. Thus, the stability of the domain structure can be estimated by calculating the energies for different numbers of domains.

Fig. 3
Energy per unit area as a function of aspect ratio.

Domain structures for various aspect ratio films were observed by the Bitter method by Nakamura, et al[2]. It was found that N changed from 1 to 2 at L/t of about 1, in a $50\text{ }\mu\text{m}$ -wide, $0.3\text{ }\mu\text{m}$ -thick amorphous CoZrNb alloy with M_s of about 10^5 A/m . The instability of the domain structure at L/t of about 1 observed in the experiment can be explained, since the energies for different numbers of domains are almost the same. The calculation suggests that

there exists an appropriate aspect ratio L/t for a stable domain structure. It is considered that a stable domain structure can be achieved by adjusting L/t to 0.6 or 1.2, because at these points the energies have a minimum value.

3.2 Output efficiency and stable domain structure

3.2.1 Dependence of anisotropic constant

The output efficiency η is calculated from Eq. (7) as a function of K_u , as shown in Fig. 4. A $50\text{-}\mu\text{m}$ wide, $40\text{-}\mu\text{m}$ long, $0.3\text{-}\mu\text{m}$ thick film is analyzed. As N changes, η changes discontinuously. For example, since the energy with $N=1$ is almost the same as that with $N=2$ at K_u of about 110 J/m^3 , N can change between 1 and 2. At the same time, η can change appreciably. As K_u approaches to 0, η increases. However, the direction of the easy axis changes by 90° when K_u becomes negative. In the negative K_u region, the domain structure changes entirely, and the output efficiency seems to be 0. Thus, the domain structure is unstable when K_u is near 0.

The reproduced voltages ξ examined by Yamakawa, et al. as a function of K_u are indicated by the filled circles in this figure[1]. The head film used in this experiment is a long $50\text{-}\mu\text{m}$ -wide and $0.3\text{-}\mu\text{m}$ -thick amorphous CoZrNb alloy, with M_s of about 10^5 A/m . The reproduced voltages ξ are measured after rerecording several times, and their scatterings are indicated by the

Fig. 4
The number of unit domains and output efficiency η as a function of anisotropic constant K_u .

vertical lines. The ζ has a maximum at K_u of about 250 J/m³, and decreases for low K_u . As K_u increases, the 180° wall width w increases according to the increase in N . Therefore, it seems that η has a maximum at $K_u=110$ J/m³. However, η changes discontinuously according to the calculation, as shown in this figure. The overall feature of η agrees with the experimentally reproduced voltage ζ . Both of them have maximum value.

Moreover, it was found that ζ becomes unstable for a K_u of less than 250 J/m³. The η is also unstable for low K_u as described above. Since the change of η relates to the change of the domain structure, it is considered that the unstable reproduced voltage for a low K_u is caused by the unstable domain structure. This can explain the experimental result.

The K_u is assumed to be controlled with an accuracy of ± 50 J/m³, as estimated from the experiments. Therefore, it is difficult to control K_u to less than 100 J/m³ in the positive region where the domain structure is stable. To obtain a head with a reproducible stability and high efficiency, it must be aimed to set K_u at 200~250 J/m³.

3.2.2 Dependence of track width

The dependence of η and stable domains structure for different track width are investigated. The output efficiencies η of 100- μ m wide-and a 20- μ m-wide films are calculated as shown in Figs.5(a) and (b), respectively. The track width t is fixed at 40 μ m. When t is 100 μ m, N changes only from 1 to 2 as K_u increases from 0 to 500 J/m³. The efficiency decreases monotonously as shown in Fig.5(a). Stable domain structure and high efficiency can be achieved even at a low K_u of 100~150 J/m³.

A film with a narrow track width is analyzed for high-track-density recording. While K_u changes from 0 to 500 J/m³, N changes from 2 to 5, as shown in Fig.5(b). The change in efficiency caused by the change in N is more appreciable. Considering the

Fig.5 Track width dependence on stability of domain structure.

control accuracy described above, K_u must be set at 350~400 J/m³ in order to obtain a stable domain structure. However, η in the K_u of 350~400 J/m³ is about 20 % less than that at a K_u of about 200 J/m³. As the track width narrows, it is necessary to control K_u more accurately, because K_u must be set at a low value, for example about 200 J/m³.

When N is equal to L/t , the output efficiency η is 0, because 180° wall width w is 0. For example, Fig.5(b) shows the case when L/t of the film is 2. When N is equal to 2, η is 0. It is desirable for L/t not to be an integer.

3.2.3 Dependence of film length

The dependence of η and stable domain structure on K_u for different track width is investigated. Films with lengths L of 100 μ m and 20 μ m are analyzed as shown in Figs.6(a) and (b), respectively. The track width t is fixed at 50 μ m.

Fig.6 Film length dependence on stability of domain structure.

When L is long, namely the aspect ratio L/t is large, N can change easily, as shown in Fig.6(a). Then, η is unstable. As L is short, N hardly changes as shown in Fig.6(b). Therefore, a high efficiency can be achieved for a low K_u . To obtain a stable, highly efficient head with a narrow track width, it is desirable for L not to be long, namely the aspect ratio of the film should not be large. The previous examination showed that the reproduced voltage was higher in the film with the low-aspect ratio[2]. However, when L/t is too small for example less than 0.3, the domain structure is unstable, as shown in Fig.3.

This analysis is available for design of a the head film with a stable domain structure and high efficiency. For example, the output efficiency can be improved when the aspect ratio is 0.4~0.6, with the track width t of $50 \mu\text{m}$, and K_u of about 110 J/m^2 .

CONCLUSION

Domain structures stability were investigated by calculating their energies for different numbers of domains N . The output efficiency η was also estimated from the domain structure. In this analysis, it was found that unstable reproduced voltage frequently observed in a low K_u region, is caused by an unstable domain structure. Using this method, the anisotropic constant K_u and the film aspect ratio with the stable domain structure, can be analyzed. To improve the stability of the domain structure in the narrow track single pole type head, K_u must be accurately controlled at a low value, and the aspect ratio should be small.

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