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인위적 반강자성체에서 자화의 시도주파수

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미소자기학 모델을 이용하여, 인위적 반강자성체에서 자화의 시도주파수에 대한 연구를 진행하였다. 다양한 일축 자기이방성, 패턴 구조 및 패턴된 시편의 에너지 장벽 크기에 대해 시도주파수를 조사하였다. 시편의 부피가 동일한 경우, 인위적 반강자성체를 구성하는 두 자성층의 결합 자기장에 따라 시도주파수가 변화하는 것을 관측하였다. 또한 에너지 장벽의 크기가 동일한 경우에도, 일축 자기이방성에 따라 시도주파수가 매우 크게 변하는 사실을 알게 되었다.

주제어 : 시도주파수, 인위적 반강자성체, 미소자기학

Attempt Frequency of Magnetization in Synthetic Antiferromagnet

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Solving the stochastic Landau-Lifshitz-Gilbert equation numerically, we investigate the attempt frequency of magnetization in synthetic antiferromagnet (SyAF). The attempt frequency is estimated while varying the uniaxial anisotropy constant, the energy barrier and the geometry of a magnetic layer. It is found that the attempt frequency is decreased for the same magnetic volume by increasing the asymmetry of the geometry in the high damping region. Also, even for a constant height of energy barrier, the attempt frequency can vary dramatically with uniaxial anisotropy constant.

Keywords : attempt frequency, synthetic antiferromagnet layer

1. Introduction

The thermal agitation of a magnetization becomes important as the magnetic volume of a unit cell in storage devices such as the hard disk drive decreases. The thermal agitation hinders a preservation of information in device because it can cause a spontaenous reversal of magnetization direction from one stable state to another. From the view point of application, it is necessary that the magnetic storage devices such as the hard disk drive [1, 2] and magnetic random access memory (MRAM) utilizing the spin-transfer torque [3-5] has a high thermal stability. The thermal stability is characterized by the thermal relaxation time τ of the magnetization. The thermal relaxation time τ is a statistical time for which the magnetization changes from an initial state to another minimum state through the energy barrier. It is described by the Arrhenius-Néel law [6], $\tau = f_0^{-1}\exp(E_b/k_BT)$ where f_0 is the attempt frequency, E_b is the energy barrier, k_B is the Boltzmann constant, and T is the temperature.

The attempt frequency f_0 is generally assumed as a constant in the experimental studies, but is a function of many parameters such as the damping constant, the energy barrier, and so on [7]. For various symmetries of the potential landscape, theoretical equations of the attempt frequency for the magnetization in a single ferromagnet have been proposed [8, 9]. Recently we confirmed that the universal theoretical equation is valid using numerical study with the stochastic Landau-Lifshitz-Gilbert (LLG) equation [10]. However, there has been no study on the attempt frequency of the synthetic antiferromagnet (SyAF) structure. In the SyAF structure, two ferromagnetic layers separated by a non-magnetic layer such as Ru maintain antiferromagnetic coupling by the Ruderman-Kittel-Kasuya-Yosida (RKKY) interaction [11]. The SyAF structure has been used as a pinned layer in magnetic recording heads or memories in order to minimize the dipolar field and stabilize the

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pinned layer magnetization. Recently, the SyAF structure was adopted as a free layer in MRAM because of its better stability.

In this work, we perform numerical simulations of the thermally activated switching of SyAF based on the stochastic LLG equation. We investigate the attempt frequency varying the damping constant, the thickness of a ferromagnetic layer and the uniaxial anisotropy constant.

2. Numerical Model

The effect of the thermal agitation on the magnetization is described by LLG equation.

$$\frac{d\mathbf{M}}{dt} = -\gamma\mathbf{M}\times\mathbf{H}_{eff} + \frac{\alpha}{M_S}\mathbf{M}\times\frac{d\mathbf{M}}{dt}, \tag{1}$$

where **M** is the magnetization vector, γ is the gyromagnetic ratio, $\mathbf{H}_{eff}$ is the effective magnetic field including the uniaxial anisotropy field, the shape anisotropy field, the magnetostatic field, the RKKY interaction field and the thermal fluctuation field, α is the Gilbert damping constant, and M_S is the saturation magnetization. We assume that the magnetic cell has a rectangular shape. We use the temperature of 300 K and the thickness of Ru of 0.7 nm. In the range of this Ru thickness, the experimental result shows that exchange coupling constant J_{ex} is 0.1 erg/cm^2 with antiferromagnetic coupling [12].

We estimate the probability of switching P_{SW} as a function of switching time t by counting the number of successful switching out of 500 switching events. The attempt frequency is obtained by fitting numerical results to the Arrhenius-Néel exponential decay $P_{SW} = 1 - \exp[-f_0 t\exp(-E_b/k_BT)]$ as shown in Fig. 1. In order to estimate the energy barrier E_b in SyAF structure, we use Stoner-Wohlfarth model that describes the magnetic energy in a single domain [13]. It is reasonable for the magnetic cell size we assume. The total magnetic energy E (per unit area) includes the uniaxial anisotropy energy E_u, the shape anisotropy energy E_{sh}, the magnetostatic energy E_{ms} and the RKKY exchange coupling energy E_{ex}, and it is defined as

$$E = E_u + E_{sh} + E_{ms} + E_{ex} \tag{2}$$

and

$$E_u = K_{u1}t_1\sin^2\theta_1 + K_{u2}t_2\sin^2\theta_2,$$
$$E_{sh} = K_{sh1}t_1\sin^2\theta_1 + K_{sh2}t_2\sin^2\theta_2,$$
$$E_{ms} = \frac{1}{2}M_{s1}Ms2[t_2(N_x^{1\to2}\cos\theta_1\cos\theta_2 + N_y^{1\to2}\sin\theta_1\sin\theta_2) + t_1(N_x^{2\to1}\cos\theta_1\cos\theta_2 + N_y^{2\to1}\sin\theta_1\sin\theta_2)],$$
$$E_{ex} = J_{ex}\cos(\theta_1 - \theta_2),$$

where θ_1 and θ_2 are the magnetization angle of the bottom layer and the top layer with respect to the easy axis (x axis), t_1 (t_2) is the thickness of the bottom layer (the top layer), M_{s1} (M_{s2}) is the magnetization of the bottom layer (the top layer), K_{u1} (K_{u2}) is the uniaxial anisotropy constant of the bottom layer (the top layer), K_{sh1} (K_{sh2}) is the shape anisotropy constant of the bottom layer (the top layer), and $N_x^{i\to j}$ ($N_y^{i\to j}$) is the magnetostatic coupling factor from layer i to j along the x (y) axis. In numerical calculation, we assume that two magnetic layers are the same materials ($K_{u1} = K_{u2} = K_u$, $M_{s1} = M_{s2} = M_s$).

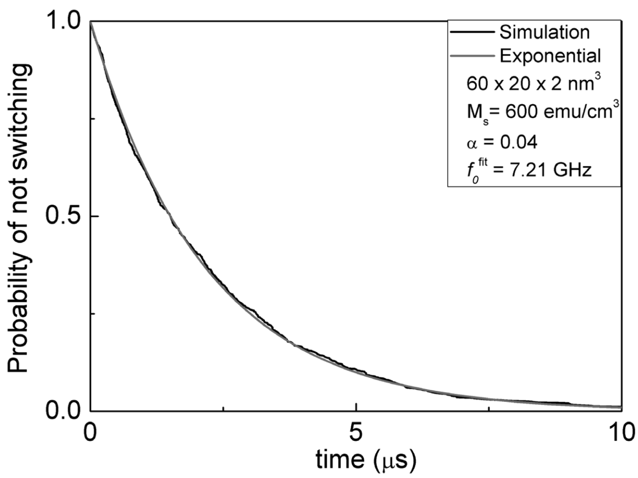

Fig. 1. Probability of not switching ($1 - P_{SW}$) versus magnetization switching time at $\alpha = 0.04$ (magnetic cell size: 60 × 20 × 2 nm^3).

3. The Attempt Frequency of Magnetization in SyAF Layer

We compare the attempt frequency of a single layer with that of SyAF layer. Fig. 2 shows an example of the attempt frequency of SyAF free layer and single free layer as a function of the damping constant. The geometry of the magnetic layer of a single cell is 60 × 20 × 2 nm^3 (length × width × thickness). In SyAF structure, the bottom layer and the top layer have the same size with a single cell (60 × 20 × 2 nm^3). The uniaxial anisotropy constant K_u is zero in a single layer and SyAF layer. We use 600 emu/cm^3 for M$_s$. The thermal stability factor E_b/k_BT is 9.96 in a single layer and 9.66 in SyAF layer. For a similar energy barrier, SyAF structure shows a higher attempt frequency than a single ferromagnet. It is caused by the strong coupling field due to the RKKY and magnetostatic interactions between the two ferromagnetic layers. This coupling field increases the attempt frequency

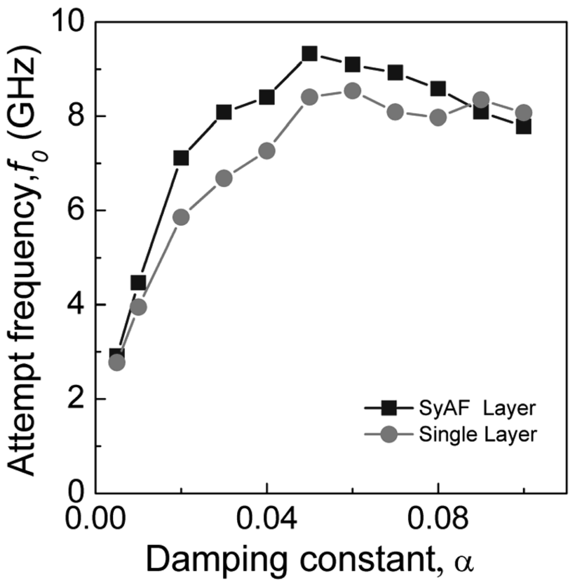

Fig. 2. The attempt frequency as a function of the damping constant for a single layer and SyAF layer. Dimensions of samples and parameters are given in the text.

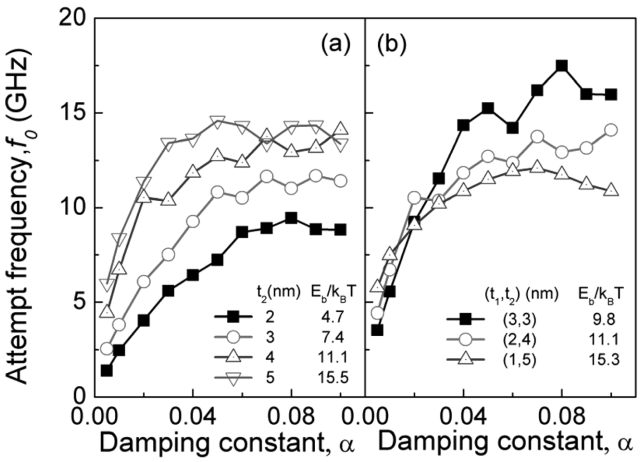

Fig. 3. The attempt frequency as a function of the damping constant for several SyAF layer. (a) t_2 is varied from 2 nm to 5 nm and t_1 is fixed at 2 nm. (b) The sum of t_1 and t_2 is fixed at 6 nm. Dimensions of samples and parameters are given in the text (M_s = 600 emu/cm^3).

of SyAF layer than that of a single layer.

To investigate the effect of the coupling field on attempt frequency in SyAF layer, we calculate the attempt frequency of various sized SyAF layers. Fig. 3(a) shows the attempt frequency of various sized SyAF layers as a function of the damping constant. The area of two layers is 30 × 10 nm^2 and the thickness of the bottom layer t_1 is fixed at 2 nm. We vary the thickness of the top layer t_2 from 2 nm to 5 nm. We use 600 emu/cm^3 for M_s and zero for K_u. We

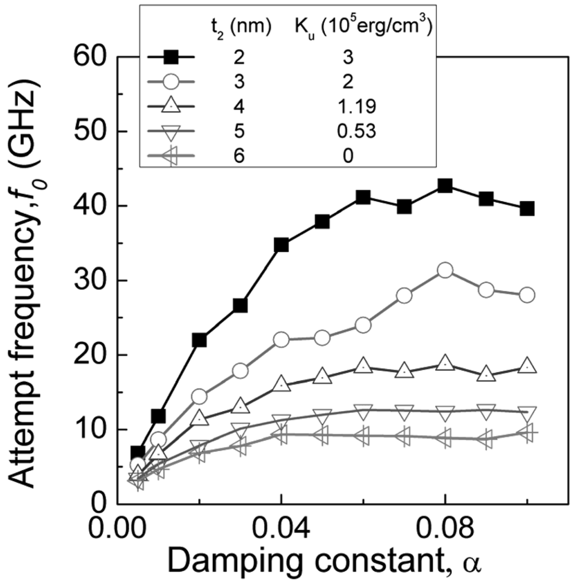

Fig. 4. The attempt frequency as a function of the damping constant for several SyAF layer. t_2 is varied from 2 nm to 6 nm and t_1 is fixed at 2 nm. K_u is given to each SyAF layer. Dimensions of samples and parameters are given in the text (M_s = 450 emu/cm^3).

see that the attempt frequency increases as t_2 increases. As shown Fig. 3(a), the energy barrier is increased linearly with increasing t_2 due to the increase in the effective magnetic volume. The attempt frequency is proportional to the energy barrier in the low damping region. In the high damping region, the increasing rate of attempt frequency with the energy barrier is reduced. Fig. 3(b) shows the attempt frequency as a function of the damping constant with fixed magnetic volume. The sum of t_1 and t_2 is fixed at 6 nm. For the same effective magnetic volume, the energy barrier is increased due to the coupling field in SyAF free layer. As the symmetry of geometry between the bottom layer and the top layer is broken, the magnetization in SyAF layer becomes more stable due to the asymmetrical coupling field. In the low damping region, the attempt frequency is increased with increasing of the energy barrier. In contrast, the attempt frequency is decreased with increasing of the energy barrier in the high damping region.

Fig. 4 shows the dependency of the uniaxial anisotropy K_u on attempt frequency in SyAF free layer. We vary t_2 from 2 nm to 6 nm and fix t_1 at 2 nm. The area of two layers is 30 × 10 nm^2. We use 450 emu/cm^3 for M_s. The thermal stability factor E_b/k_BT is from 11.4 to 11.5 in all five samples. Several different anisotropy constants are used for adjusting the energy barrier. All cases have the similar energy barrier, but the attempt frequency varies dramatically with K_u, especially in high damping region. As K_u increases by the factor of 2, the attempt frequency increases by about the factor of 1.5.

4. Conclusion

We investigate the effect of the geometry, the unaxial anisotropy constant and the energy barrier on the attempt frequency in SyAF structure. The thermal relaxation time is not determined only by the energy barrier, but also depends on the attempt frequency. For the same energy barrier, the attempt frequency is found to vary significantly with the uniaxial anisotropy and damping constant. Therefore, the study on the attempt frequency should be preceded to design experiments and interpret experimental results.

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