SWITCHING AND HYSTERESIS CHARACTERISTICS OF EXCHANGE COUPLED COMPOSITE SOFT MAGNETIC FILM

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Synopsis

Theoretical calculations are carried out on the switching characteristic of the composite film consisting of the two uniaxial soft magnetic films which are formed in close molecular contact with each other and whose magnetic easy directions are perpendicular to each other. The result shows that such a composite film has a potential for a non-destructive-read-out (NDRO) computer memory element.

1. Introduction

Theoretical studies on the exchange coupled composite film will be given in the present paper. Throughout this paper, the term composite film means a magnetic film composed of two soft magnetic layers which are formed in close molecular contact with each other, and whose magnetic easy axes are different in direction with each other. In such a film, the magnetic anisotropy will make the direction of the magnetization of each layer parallel to each magnetic easy direction. The exchange coupling, on the other hand, tends to make the magnetization directions of the two layers in parallel. Therefore, the magnetization direction of this composite film will not be uniform across the thickness of the film and will change gradually from the top of the film to the bottom making fan like distribution as seen in Fig. 1 (a). If we apply the magnetic field anti-parallel to the mean magnetization direction of such film, the magnetization may reverse by the fanning process[1], namely the upper magnetization rotates in one direction and the lower in opposite direction. Furthermore, after the removal of the reverse field, the magnetization is expected to back to the initial state by the exchange coupling force. In this meaning, this film can be said as unidirectional film. Actually, these fanning magnetization reversal and unidirectional property have been demonstrated by somewhat different way in single layered permalloy film[2]. In this way, this composite film may have the potential as the NDRO memory element.

In this paper, the theoretical calculation is carried out on the hysteresis and switching characteristics of the composite film, in which the anisotropy of each layer is assumed to be uniaxial. The result shows that the composite film is actually applicable as the NDRO element as expected, if the thickness is in the appropriate range.

2. Theoretical Calculations

(*a*) *General Formulatin*—The cartesian coordinate system (x, y, z) is used with

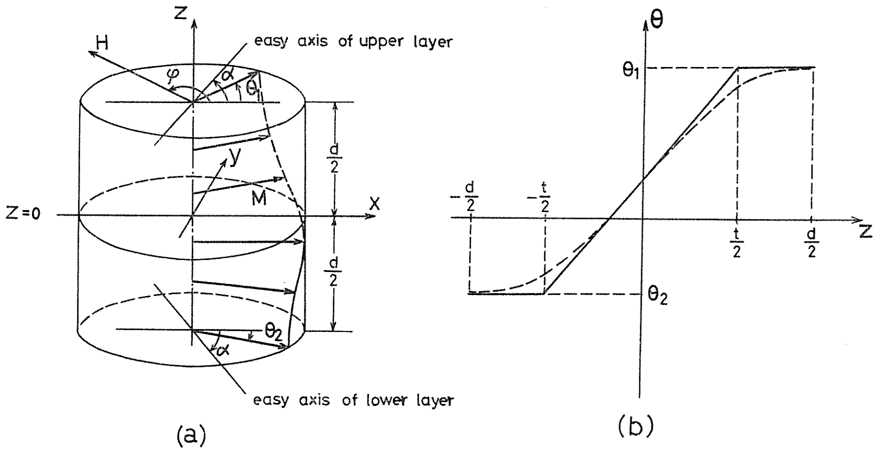

FIG. 1. The magnetization distribution of the composite film.

the z-axis pointing normal to the plane of the composite film and with the boundary surface of the two layer at $z=0$. Therefore, the magnetization of the two layers are confined within the x-y plane. Without loss of generality, the easy axes of the respective two layers will be assumed to form angles α and $-\alpha$ with the x-axis. For simplicity of calculation, we shall assume that the exchange constants A, the thicknesses d, the uniaxial anisotropy constants K_u, and the saturation magnetizations M of the two layers are equal respectively. The external field H is applied at the angle φ with the x-axis in the x–y plane. The direction of the magnetization θ will change continuously from θ_1 to θ_2 along the z-axis as shown in Fig. 1 (a), where θ_1 and θ_2 are the directions of the magnetizations at the top and at the bottom surfaces of the film respectively. The values of θ_1 and θ_2 should be determined by minimizing the total free energy E. In this case E is composed of the exchange energy E_{ex}, the anisotropy energy E_a, and the field energy E_h which are expressed as follows:

$$E_{ex} = \int_{-d/2}^{d/2} A\left(\frac{d\theta}{dz}\right)^2 \frac{dz}{d} \tag{1}$$

$$E_a = \int_{-d/2}^{0} K_u \sin^2(\alpha+\theta)\frac{dz}{d} + \int_{0}^{d/2} K_u \sin^2(\alpha-\theta)\frac{dz}{d} \tag{2}$$

$$E_h = \int_{-d/2}^{d/2} MH\cos(\varphi-\theta)\frac{dz}{d}. \tag{3}$$

For the purpose of simplifying the above energy calculations, we assume that the direction of the magnetization varies linearly with z as shown by the solid line in Fig. 1 (b), though it is actually considered to vary in somewhat different manner as shown by the broken line in Fig. 1 (b). Then the total energy per unit volume normarized by K_u is given as

$$\varepsilon = E/K_u = \frac{A}{K_u d^2}\cdot\frac{(\theta_1-\theta_2)^2}{r} - \left[\frac{(1-r)}{4}\left\{\cos 2(\alpha+\theta_2) + \cos 2(\alpha-\theta_1)\right\}\right.$$
$$\left. + \frac{r}{4(\theta_1-\theta_2)}\left\{\sin 2\left(\alpha+\frac{\theta_1+\theta_2}{2}\right) - \sin 2(\alpha+\theta_2) - \sin 2(\alpha-\theta_2) + \sin 2\left(\alpha-\frac{\theta_1+\theta_2}{2}\right)\right\}\right]$$

$$-\left[h(1-r)\{\cos(\varphi-\theta_2)+\cos(\varphi-\theta_1)\}+\frac{2hr}{\theta_1-\theta_2}\{\sin(\varphi-\theta_2)-\sin(\varphi-\theta_1)\}\right] \quad (4)$$

where $h=H/H_k$, $H_k=2K_u/M$, and $r=t/d$. The first term results from the exchange energy, the second the uniaxial anisotropy energy, and the third the field energy. The values of θ_1, θ_2 and r corresponding to the equilibrium distribution was determined numerically by minimizing the normarized total energy ε for each value of h.

(*b*) *B-H Characteristic*—Now we can calculate the theoretical B-H characteristic by the use of θ_1 and θ_2 determined above. The total component of the magnetization parallel to the applied field is given by

$$B=\int_{-d/2}^{d/2} M\cos(\varphi-\theta)dz$$

$$=\frac{1}{2}B_s(1-r)\{\cos(\varphi-\theta_2)+\cos(\varphi-\theta_1)\}+\frac{B_s r}{\theta_1-\theta_2}\{\sin(\varphi-\theta_2)-\sin(\varphi-\theta_1)\} \quad (5)$$

where $B_s=Md$. Some results of numerical calculation are shown in Fig. 2 with $\alpha=45°$, that is, with the easy axes of the two layers at a right angle to each other. In the figure, the direction of the applied field φ is varied as a parameter. It is noted that the remanent magnetization M_r has single value with $\varphi=180$ degrees. This suggests that the reverse field does not disturb the initial value of M_r. If $\varphi \neq 180°$, on the other hand, the magnetization does not back to the initial state after the removal of the switching field. Since the skew is inevitable in actual film, this result means that the film can not be used as the NDRO memory element. However, this conclusion results only from the static consideration, and we forwarded our work to make clear whether this conclusion does not change in the dynamic case.

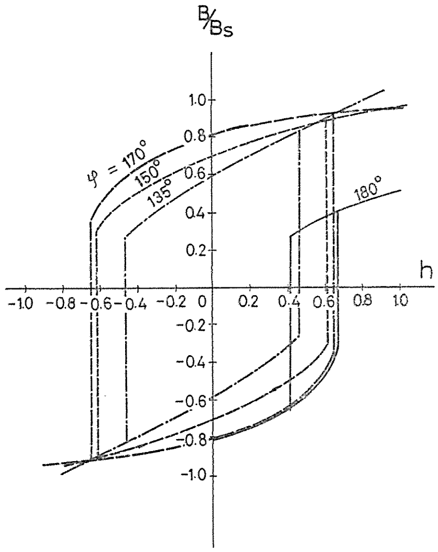

FIG. 2. The hysteresis curves of the composite film. Parameters: $A=10^{-6}$ erg/cm; $K_u=10^3$ erg/cm^3; $M=800$ Gauss; $d=2\sqrt{2}\,\mu$; $\alpha=45°$.

(*c*) *Dynamic Switching Threshold Curve*—As it is well known, the dynamic behavior of the magnetization should be examined by the use of Landau-Lifshitz or Gilbert equations. In this paper, however, we should like to discuss about the possibility of occuring the non-destructive switching for $\varphi \neq 180°$ from the free energy consideration. This is because the free energy was already calculated in the previous section.

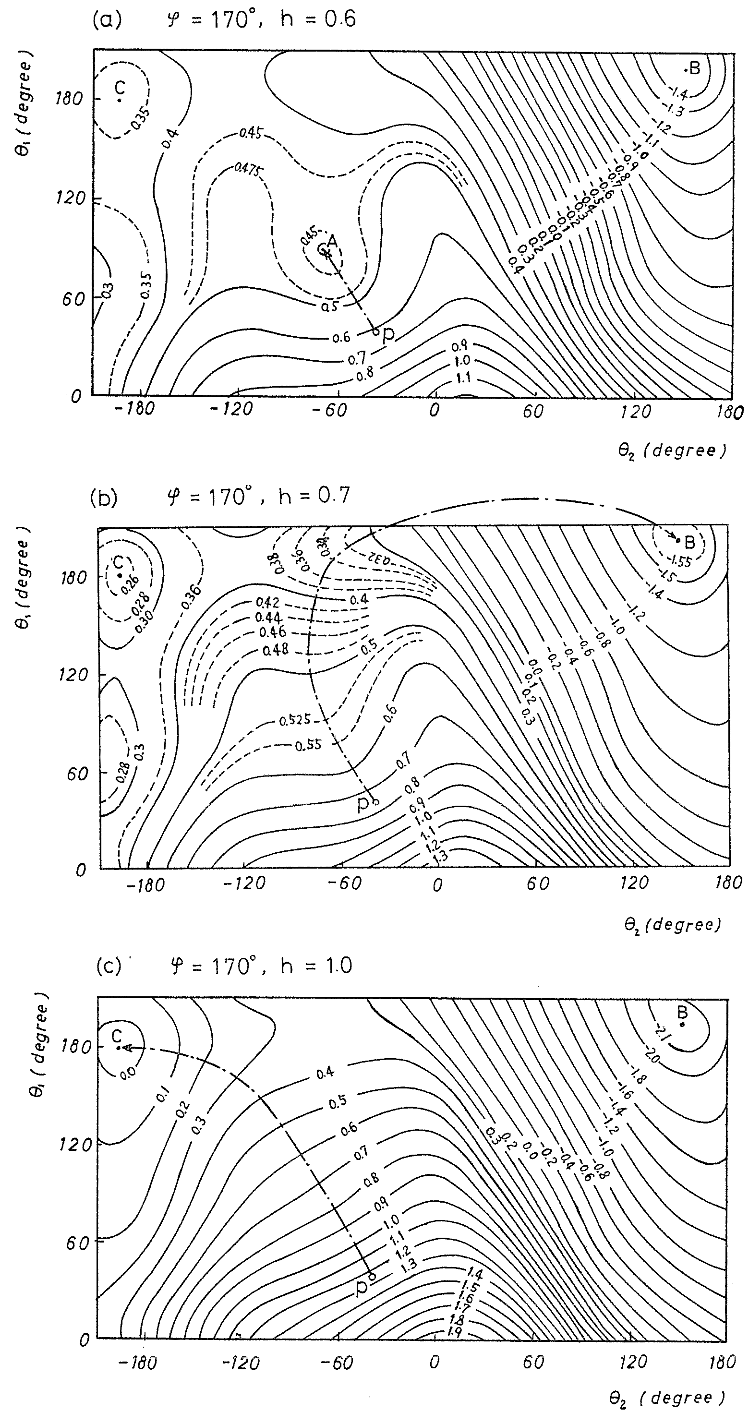

FIG. 3. The energy contour maps of the composite film.
Parameters; $A=10^{-6}$ erg/cm; $K_u=10^3$ erg/cm^3; $M=800$ Gauss; $d=2\sqrt{2}\,\mu$; $\alpha=45°$.

Here it is assumed that the pulse switching field has the risetime much shorter than the switching time of the magnetization. Then the free energy is thought to change instantantaneously from the value corresponding to $h=0$ to that of the final value of h. It is also assumed that the magnetization follows the gradient line of the free energy contour map in $\theta_1-\theta_2$ plane which corresponds to the final value of the applied pulse field h. Examples of the free energy contour maps are shown in Fig. 3, where the switching pulse field of the magnitude of 0.7, 0.8, and 1.0 are applied at $\varphi=170°$. In these figures, point P is the initial position ($h=0$) of the magnetization.

It may be estimated from these examples that there are three characteristic transitions in the composite film corresponding to three energy minimums marked as A, B, and C in Fig. 3 (a). The minimum state A shifts continuously from the initial state P with increasing h from 0, and disappears at a critical value h_{c1}. This implies that, so long as h is smaller than the critical field h_{c1}, the magnetization takes the minimum state A and that it recovers the initial state after the removal of the pulse field. If h exceeds h_{c1}, there exist now the two minimum states B and C as shown in Fig. 3 (b) and (c). This means that the magnetization jumps to B or C if $h>h_{c1}$. If we start from the point P and go along the gradient line shown as dot-and-dash in Fig. 3 (b) and (c), then we will find out that we will reach to either point B or point C according as the value of h. More precisely, we will reach to B when $h<h_{c2}$ and to C when $h>h_{c2}$. In this way, we have another critical field h_{c2} below which the magnetization jumps to the state B and above which to C.

As it is easily known from the coordinates of B, the jump to the deep minimum B corresponds to the destructive switching as in the case of the static switching. The jump to the shallow minimum C, on the other hand, corresponds to the non-destructive switching, namely the magnetizations of the two layers rotate to the opposite sense to each other and form the fan shape distribution spread nearly over 360°. The magnetization distribution recovers the initial state due to the exchange coupling effect after the removal of the pulse field as we will see later, provided that the film thicknss is not so thick enough. In Fig. 4 are shown the switching threshold fields h_{c1} for the destructive switching and h_{c2} for the non-destructive switching.

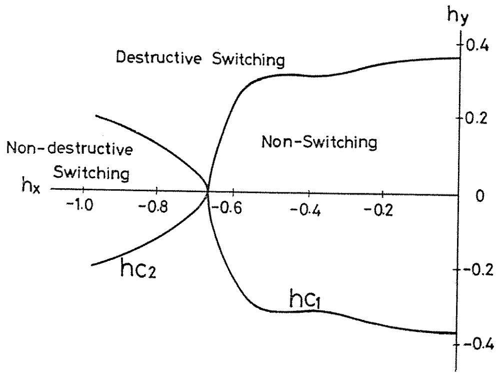

FIG. 4. The switching threshold curve of the composite film.
Parameters: $A=10^{-6}$ erg/cm; $K_u=10^3$ erg/cm; $M=800$ Gauss; $d=2\sqrt{2}\mu$; $\alpha=45°$.

(*d*) *Maximum Film Thickness for Non-destructive Switching*—Two requirements will determine the range of the thickness of the composite film over which the non-destructive switching may be applied. Firstly, the lower limit of the thickness is determined by the requirement that the magnetizations of the two layers can be distributed over a range of 360 degrees with a relatively low pulse field. This condition may be approximately the same as that the composite film is thicker than the width of the domain wall. Secondly, the upper limit of the thicknese is determined by the requirement that the magnetization fanning must return to the initial state by the exchange coupling. In other word, only one state is stable when $h=0$. The normarized energy ε is calculated as a function of θ_1 and it is shown in Fig. 5, where the film thickness is taken as a parameter and it is assumed that $\theta_2=-\theta_1$. This result gives that the composite film must be thinner than about 4 μ for this combination of film constants, namely $A=10^{-6}$ (erg/cm), $K_u=10^3$ (erg/cm^3), $M=800$ (Gauss), and $\alpha=45°$.

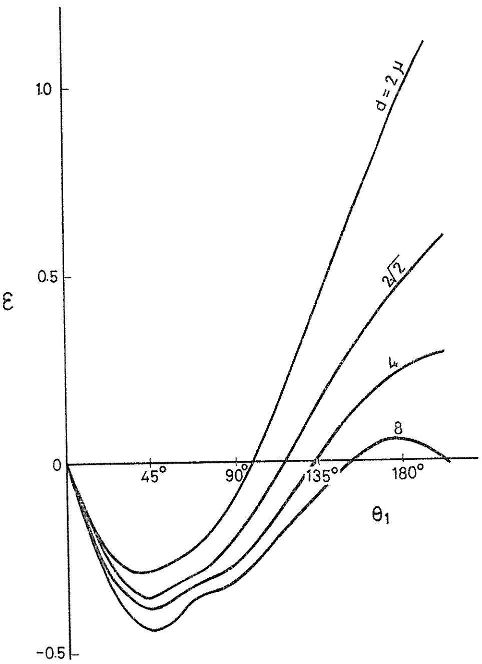

FIG. 5. The dependence of the normalized energy ε upon θ_1 with the thickness d taken as a parameter.

Parameters: $A=10^{-6}$ erg/cm; $K_u=10^3$ erg/cm^3; $M=800$ Gauss; $\alpha=45°$.

3. Discussions and Conclusions

The theoretical calculation was carried out on the hysteresis loop, the switching threshold curve, and the thickness suitable for the non-destructive switching for the composite film. The most impotant result is that the composite film of $2\mu \sim 4\mu$ in thickness has the possibility to be used as the NDRO memory element. This conclusion, however, is not decisive one because we did not use the Landau-Lifshitz equation for the dynamics of the magnetization. Neverthless, this conclusion encourages us to make further investigatien about this type of the composite film. We will report in the next report how to use this composite film in a NDRO memory system.

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