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Simulation of toggle mode switching in MRAM'S

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The magnetization switching in Stoner-like magnetic particles is one of the fundamental issues in magnetic data storage. In develop of magnetoresistance random access memory (MRAM), the theoretical studies are now concentrated in various parameters improving. Some important parameters are the range of the operating field and the switching time. The writing mode proposed by Savtchenko and co-workers is known as the toggle MRAM or toggle write mode, is essentially based on a sequence of fields applied at 45° with respect to the easy axis of an antiferromagnetically coupled system of two single domain particles. We have recently analyzed systematically systems of two magnetic moments coupled with magnetostatic interactions. In this paper we are presenting the effect of the anisotropy of each material on the switching of a SAF in a toggle mode. For the uniaxial anisotropy type analytical approach is possible and simple results and critical curves are presented. For the more general case only the micromagnetic simulation can offer results. The studies are made for different coupling constants between the two ferromagnetic layers and the results are discussed.

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1. Introduction

For increasing the operation margin of MRAM elements, actual applications use magnetic memories cells made from two ferromagnetic layers with antiferromagnetic coupling and separated from a very thin a non magnetic layer, named Synthetic Antiferromagnet (SAF).

Recently, Savtchenko and co-workers proposed a new writing method of a MRAM element, named toggle mode. [2] The "word" and "digit" field are applied sequentially with an angle of 45 degrees with respect to the easy axis of the magnetic anisotropy of memory element (Fig. 1).

An SAF element are made from two ferromagnetic layers 1 and 2 that have the thickness t_1 and t_2, magnetizations M_1 and M_2 and uniaxial anisotropy constants K_{u1} and K_{u2}. The easy axes of the two layers are parallel and antiferromagnetic coupling.

Energy density for unit area W can be expressed:

$$\begin{aligned} W = K_{u1} t_1 \sin^2\theta_1 + K_{u2} t_2 \sin^2\theta_2 - \\ - M_1 t_1 [H_x \cos\theta_1 + H_y \sin\theta_1] - \\ - M_2 t_2 [H_x \cos\theta_2 + H_y \cos\theta_2] + \\ + J\cos(\theta_1 - \theta_2) \end{aligned} \quad (1)$$

where θ_1 and θ_2 are the angle between magnetization M_1 and M_2 and easy axis for each layer, H_x and H_y are components of applied magnetic field from Ox and Oy axis and J are the antiferromagnetic coupling strength between the two layers. We chose a coordinating system in witch Ox axis coincide with easy axis and Oy axis coincide with hard axis, parallel with the layers plane.

Normalizing W by $2K_{u1}t_1$ and use identical layers for simplify the discussion ($t_1 = t_2$, $M_1 = M_2$, $K_{u1} = K_{u2}$), the free energy can be expressed as:

$$\begin{aligned} w = \frac{1}{2}\sin^2\theta_1 + \frac{1}{2}\sin^2\theta_2 - (h_x\cos\theta_1 + \\ + h_y \sin\theta_1) - (h_x\cos\theta_2 + h_y\sin\theta_2) + \\ + h_J\cos(\theta_1 - \theta_2) \end{aligned} \quad (2)$$

where all the field are normalized at the anisotropy field of layers and (h_x, h_y) are projections of applied field:

$$h_x = \frac{H_x}{H_k},\ h_y = \frac{H_y}{H_k},\ H_k = \frac{2K_{u1}}{M_1},\ h_J = \frac{J}{2K_{u1}t_1}.$$

Fujiwara and co-workers propose to study the trajectories of the field, giving a constant angle θ_1 and leaving θ_2 to be a variable and vice versa, for easily understand the response of the magnetizations to the applied vector – field in the (h_x, h_y) plane. [1] They call this trajectories "constant angle contours" and can be founded by solving the equilibrium and stability conditions:

$$w_1 = 0,\ w_2 = 0,\ w_{11} > 0,\ w_{22} > 0,$$

$$D = w_{11}w_{22} - w_{12}^2 \geq 0 \quad (3)$$

where w_1, w_2, w_{11}, w_{22} and w_{12} are the first and the second derivates of energy w with respect to θ_1 and θ_2, respectively. Expressions of h_x and h_y are:

$$\begin{cases} h_x = [\cos\theta_1\cos\theta_2(\sin\theta_2 - \sin\theta_1) + h_J(\cos\theta_1 + \\ \quad + \cos\theta_2)\sin(\theta_1 - \theta_2)] / \sin(\theta_1 - \theta_2) \\ h_y = [\sin\theta_1\sin\theta_2(\cos\theta_2 - \cos\theta_1) + h_J(\sin\theta_1 + \\ \quad + \sin\theta_2)\sin(\theta_1 - \theta_2)] / \sin(\theta_1 - \theta_2) \end{cases} \quad (4)$$

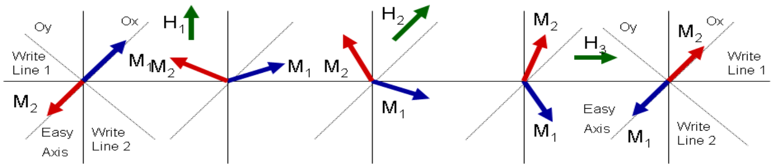


Fig. 1. Toggle mode switching proposes by Savtchenko.

It is a good idea to use instead of the (θ_1, θ_2) coordinates for the orientations of the moments of the layers the system (ξ, η), where:

$$\xi = \frac{\theta_1 + \theta_2}{2} \text{ and } \eta = \frac{\theta_2 - \theta_1}{2}. \quad (5)$$

With these new coordinates, the equilibrium conditions give the general equation of a critical curve, as:

$$h_x(\xi,\eta) = \frac{\cos\xi}{\cos\eta}\left(\sin^2\xi + (2h_J - 1)\cos^2\eta\right)$$
$$h_y(\xi,\eta) = \frac{\sin\xi}{\cos\eta}\left(-\cos^2\xi + (2h_J + 1)\cos^2\eta\right) \quad (6)$$

For the $\eta \to 0$ limit one obtains the saturation critical curve:

$$h_x(\xi) = -\cos^3\xi + 2h_J\cos\xi$$
$$h_y(\xi) = +\sin^3\xi + 2h_J\sin\xi \quad (7)$$

That shows a strong resemblance to the parametric equations of the Stoner Wohlfarth particle, with a correction due to the coupling between the layers.

If the parameters of the two layers are identical, constant angle contours are identical for both layers. Exterior envelope represent the critic curve for saturation and the interior envelop represent the critic curve for switching, curve named "astroid".

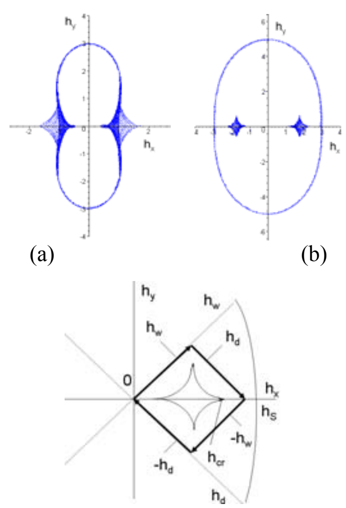


Fig. 2. Constant angle contour for (a) $h_J = 1$ and (b) $h_J = 2$ where θ_1 and θ_2 vary from 0^0 to 180^0. (c) Schematic representation of applied magnetic fields trajectory for toggle mode switching. The "word" and "digit" field applied and interrupt sequential are indicated.

In actual applications of MRAM devices H_w and H_d - "word" and "digit" magnetic fields – are equally. We can represent a trajectory for magnetic applied field to the MRAM cell, where h_w and h_d are "word" and "digit" field normalized at the anisotropy field H_{k1}.

2. Study of toggle mode switching consider the second term of anisotropy energy

If we take into consideration the second term from series expansion for the magneto-crystalline uniaxial anisotropy, the free energy can be expressed as:

$$w = \frac{1}{2}\sin^2\theta_1 + \frac{1}{2}\sin^2\theta_2 + \frac{1}{4}k_2\sin^4\theta_1 +$$
$$+\frac{1}{4}k_2\sin^4\theta_2 - \left(h_x\cos\theta_1 + h_y\sin\theta_1\right) - \quad (8)$$
$$-\left(h_x\cos\theta_2 + h_y\sin\theta_2\right) + h_J\cos(\theta_1 - \theta_2)$$

where $k_2 = \frac{K_2}{K_1}$, K_2 is the second term of anisotropy energy.

From equilibrium conditions, and take into considerations the (ξ, η) system from (3), the general equations of critical curves depend of k_2 term:

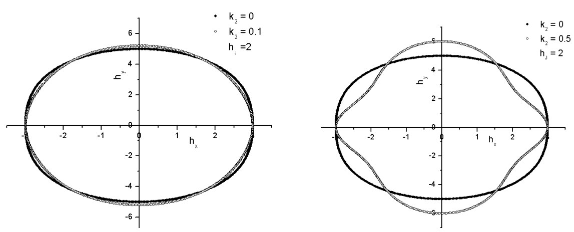
$$h_x(\xi,\eta) = \frac{\cos\xi}{\cos\eta}\{\sin^2\xi[1 + 2k_2(\cos^2\xi + 3\cos^2\eta -$$
$$-4\cos^2\xi\cos^2\eta)] + [2h_J - 1 - 2k_2(\cos^2\xi +$$
$$+3\cos^2\eta - 4\cos^2\xi\cos^2\eta)]\cos^2\eta\}$$
$$h_y(\xi,\eta) = \frac{\sin\xi}{\cos\eta}[-\cos^2\xi[1 + 2k_2(\cos^2\xi + \cos^2\eta - \quad (9)$$
$$-4\cos^2\xi\cos^2\eta)] + [2h_J + 1 + 2k_2(\cos^2\xi +$$
$$+\cos^2\eta - 4\cos^2\xi\cos^2\eta)]\cos^2\eta\}$$

For the $\eta \to 0$ limit, the saturation critical curves are expressed by:

$$h_x(\xi) = -\cos^3\xi(1 + 6k_2\sin^2\xi) + 2h_J\cos\xi$$
$$h_y(\xi) = +\sin^3\xi(1 - 4k_2 + 6k_2\sin^2\xi) + \quad (10)$$
$$+2h_J\sin\xi$$

which are similar with express of critical field vector from Stoner Wohlfarth theory, with a correction due to the coupling between the layers.

If we represent critic curve in (h_x, h_y) coordinates for $k_2 = 0$ and for $k_2 \neq 0$, we observe that it is a difference between critic curve for case when we ignore the second term of series expansion of the anisotropy free energy and critic curve for the case when we take into consideration the second term of anisotropy energy density (Fig. 3).



(a) (b)

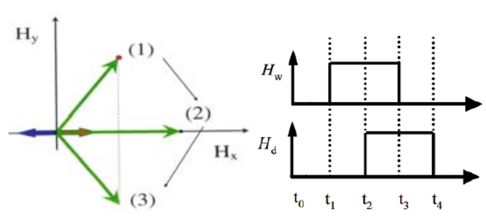
Fig. 3. Difference between critical curve in (h_x, h_y) coordinates for an normalized interlayer coupling field h_J =2 (a) case of k_2 = 0 and k_2 = 0.1; (b) case of k_2 = 0 and k_2 =0.5.

In process of material selection for utilization in technical process of MRAM cell creation, must be taking into consideration influence of the second term of anisotropy energy. This term could change the shape of critical curve when its value is significant and the shape of operating field margin.

3. Study of toggle mode switching consider LLG model

The study of switching or non-switching M_1 and M_2 magnetizations of the layers can be made with Landau – Lifshitz – Gilbert equation. We can consider the simply case of the two magnetic moments antiferromagnetic coupling, with H_J the coupling field, antiparallel oriented on Ox axis. We apply to these magnetizations a succession of exterior magnetic fields, 45^0 oriented from easy axis.

We take into consideration the case in witch material dumping constant α are small enough so that magnetizations reach equilibrium in a time field applied period ($\alpha = 0.008$). The angle of magnetization at the end of a period represents the start angle of magnetization for the next time period.



(a) (b)

Fig. 4. (a) The succession of "word" and "digit" field applied for toggle mode switching. (b) Two pulses with phase differences that produce h_w and h_d applied field.

The applied fields are apply in Oxy plane and are characterized by $\left(H_x, H_y\right)$ values, $H=\sqrt{H_x^2+H_y^2}$. The value of the applied angle is $tg\theta = \frac{H_y}{H_x}$.

Solving the LLG equations for the two magnetizations, we can obtain the precise domain of switching. The light points represent the applied exterior magnetic field for witch the switching take place. The dark point represents the applied exterior field for witch the switching of magnetizations is not produce.

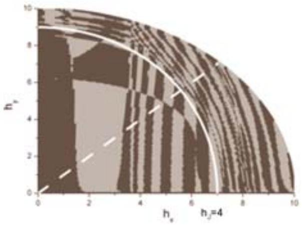


Fig. 5. The switching diagram of a single MRAM for $h_J = 4$. Light areas correspond to switched states while dark areas correspond to not-switched states.

In the figure, the critical curve is shown at the line at 45^0 represents the actual direction used in the toggle mode. One can observe that in the case of applied fields higher than the saturation field, the micromagnetic simulation detects a noisy area which can't be observed in the critical curve approach. This approach can be misleading in certain cases due to the simplifications used in this case.

4. Conclusion

The constant angle contour helps in understanding the comportment of the two magnetizations and to detect the shape of astroids who leads the applied of "word" and "digit" field for different parameters of the two layers.

The second term of anisotropy energy could change the shape of critical curve and the shape of operating field margin when its value is significant

The LLG simulations present detailed the switching and non-switching points for different values of exterior applied magnetic field and for different angle.

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