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Antiferromagnetic coupling in ferromagnetic/ferrimagnetic and ferromagnetic/antiferromagnetic thin films

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Abstract

Nowadays, magnetic coupling is wildly used in magnetic thin films, e.g. the interface in a reading sensor of magnetic recording head. In this paper, we present the antiferromagnetic coupling effects of bilayer thin films in two cases: (i) ferromagnetic/ferrimagnetic and (ii) ferromagnetic/antiferromagnetic. In the first case, the Object Oriented MicroMagnetic Framework (OOMMF) was used to simulate the micromagnetic structure. According to the results, the magnetic property of Ni/TbFeCo bilayer shows the negative coercivity because of strong antiferromagnetic coupling. In the second case, Stoner-Wohlfarth model was used in the modelling of ferromagnetic/antiferromagnetic layers. The results suggest that the positive exchange bias is contributed by the weak antiferromagnetic coupling. In conclusion, the results lead to development of magnetic thin films in future read head technology.

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Keywords: Antiferromagnetic coupling; Negative coercivity; Positive exchange bias

1. Introduction

Magnetic coupling at interface of magnetic thin film multilayer is used to improve magnetic property for specific applications. The property is unlike in the case of a conventional magnetic material. Magnetic coupling has two types - ferromagnetic coupling and antiferromagnetic coupling. They are widely applied for technological applications, such as giant magnetoresistance (GMR) using antiferromagnetic coupling at interface of the magnetic thin film multilayer in order to increase areal density from 1-5 Gb/in^2 up to 10-70 Gb/in^2 [1]. Antiferromagnetically coupled (AFC) media is helped to maintain thermal stability even for lower values of $M_r\delta$ [2]. A nearly single-domain state with improved exchange and anisotropy fields, and high thermal stability have been achieved on synthetic antiferromagnetic coupled films (SAF) [3]. In addition, the magnetic coupling between hard/soft magnetic layers in exchange coupled composite media is used to reduce switching field [4].

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Nowadays, many research groups have been focused on the magnetic coupling in magnetic thin films. Shan *et al.* [5] found the negative exchange bias of ferromagnetic/antiferromagnetic bilayer because of weak ferromagnetic coupling. Furthermore, Liu *et al.* studied the negative coercivity of ferromagnetic/ferrimagnetic/ferromagnetic trilayer because of strong antiferromagnetic coupling [6]. Therefore, the magnetic coupling is very important to develop the magnetic property of magnetic thin films.

For above reasons, magnetic coupling is particularly interesting to study. Such properties make the bilayer an interesting candidate for technological magnetic applications. The main propose of this paper focuses on the effect of antiferromagnetic coupling between interfaces of bilayer magnetic thin films. In the present work, modeling contributions have been made in two areas: (i) Object Oriented MicroMagnetic Framework (OOMMF) simulation for ferromagnetic/ferrimagnetic layers and (ii) analytical method calculation for ferromagnetic/ antiferromagnetic layers.

This paper is divided into 4 sections. Section 2 describes about modeling of magnetic thin film structures. Section 3 is the results and discussions for ferromagnetic/ferrimagnetic and ferromagnetic/antiferromagnetic bilayer thin films. Finally, section 4 is conclusion of this work.

Nomenclature

FM	Ferromagnetic material
AFM	Antiferromagnetic material
M_{FM} , M_{AFM}	The magnetization of ferromagnetic and antiferromagnetic materials, respectively
H	Applied external field
H_c	Coercivity
H_{ex}	The positive exchange bias field
J	Magnetic coupling constant
K_1	Magnetic anisotropy constant
A	Exchange stiffness constant
M_s	Saturation magnetization
t	The thickness of layer
β	The angles of the M_{FM} with respect to the easy axis
α	The angles of the M_{AFM} with respect to the easy axis
θ	The angles of the H with respect to the easy axis
E_B	Energy barrier height

2. Modeling of Magnetic Thin Film Structures

2.1 Ferromagnetic/Ferrimagnetic structure

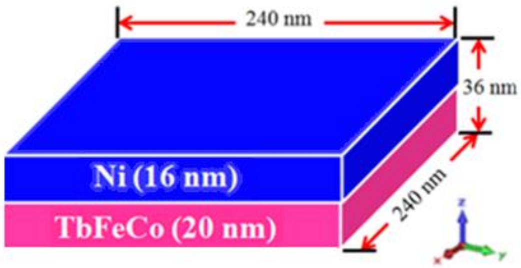


Fig. 1. Structure of Ni (16 nm)/TbFeCo (20 nm) thin film

OOMMF [7] was used to analyze antiferromagnetic coupling between ferromagnetic/ ferromagnetic layers. It is widely used to analyze the three dimensional micromagnetic simulations based on LLG equation and calculated by using finite different time domain.

The magnetic materials are Ni (soft ferromagnetic) and TbFeCo (hard ferrimagnetic). The structure has dimension of 250×250×36 nm^3 as shown in Fig. 1. The magnetic parameters of Ni and TbFeCo are in Table 1.

Table 1. Magnetic parameters of Ni and TbFeCo [6]

Magnetic material	K_1 (MJ/m^3)	A (pJ/m)	M_s (kA/m)
Ni	0	9	470
TbFeCo	0.25	13	250

2.2 Ferromagnetic/Antiferromagnetic structure

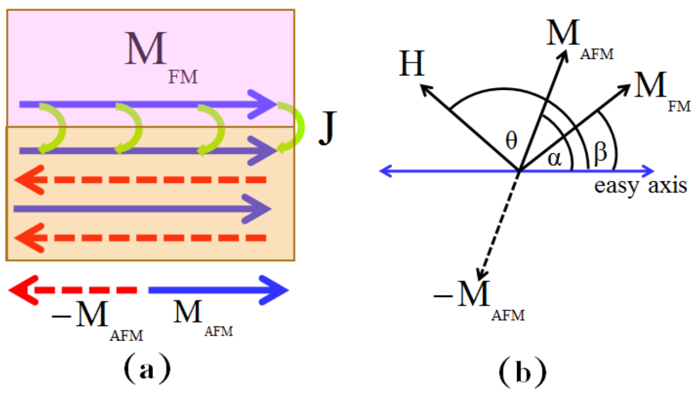


Fig. 2. (a) Schematic of coupled ferromagnetic/antiferromagnetic thin film; (b) configuration of magnetization, M_{FM}, M_{AFM} and applied field, *H*, with respect to easy axis [5]

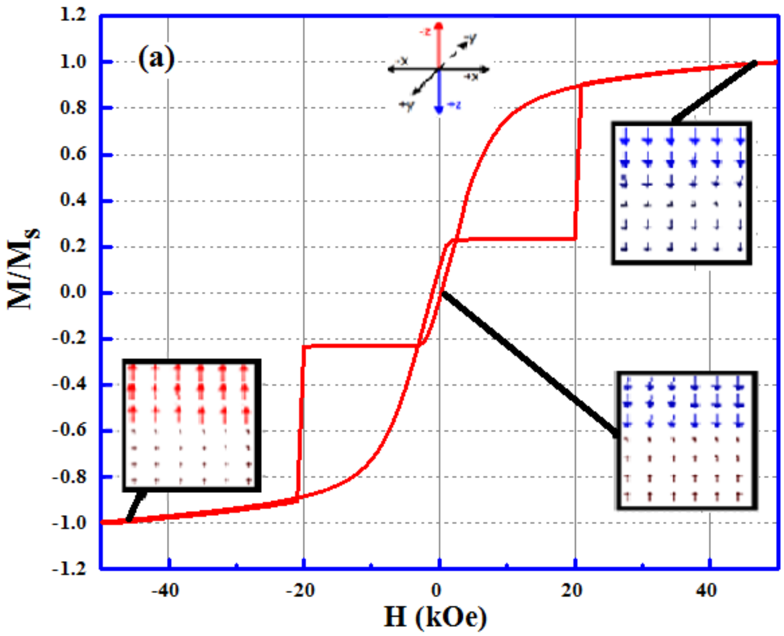
The ferromagnetic/antiferromagnetic layers model has been established based on the Stoner–Wohlfarth model [8] to analyze the effects of exchange-bias coupling and the applied field. Analytical solutions indicated the correlation between the magnetic and structural properties of the bilayer thin films have been derived. These solutions are useful for understanding the structural and magnetic properties of exchange bias.

3. Results and Discussions

3.1 Ferromagnetic/Ferrimagnetic layers

Fig. 3 (a) shows the hysteresis loop for bilayer of Ni/TbFeCo. The exchange stiffness constant is about -18 pJ/m, where "-" means antiferromagntic coupling. It suggests that increasing of antiferromagnetic coupling at interface causes the negative coercivity. Both the magnetization of Ni and TbFeCo layer will saturate with the applied field higher than 20 kOe. At reducing the applied field, the magnetization of Ni will be rotated to the reversed direction with the applied field due to the antiferromagnetic coupling in the interface while the TbFeCo will be not rotated. As the magnetic moment of Ni is larger than the magnetic moment of TbFeCo, the net magnetization of the bilayer tends to be negative. It is called negative coercivity for bilayer magnetic thin films.

Fig. 3 (b) shows the coercivity of bilayer and trilayer. It indicates that bilayer need the coupling higher than trilayer to reach negative coercivity because bilayer has one interface to couple less than trilayer (two interfaces). Therefore, bilayer and trilayer have the negative coercivity at exchange stiffness constant about -18 and -6 pJ/m, respectively.



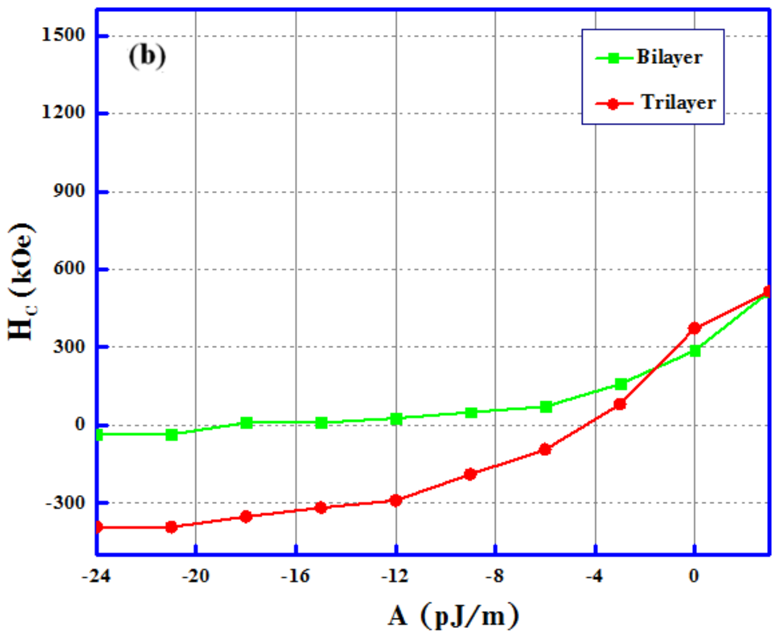


Fig. 3. (a) The hysteresis loop for Ni/TbFeCo bilayer with A= -18 pJ/m; (b) dependence of coercivity on exchange stiffness constants for Ni(8nm)/TbFeCo(20nm)/Ni(8nm) versus Ni(16nm)/TbFeCo(20 nm)

3.2 Ferromagnetic/Antiferromagnetic layers

The thin FM layer is assumed to be coupled with an AFM underlayer by exchange-bias as shown Fig. 2 (a) and the configuration of moment and H-field is shown in Fig. 2 (b). Energy of the structure consists of Zeeman energy ($HM_{FM}t_{FM}\cos(\theta-\beta)$), exchange energy ($|J|\cos(\beta-\alpha)$), and anisotropy energy for ferromagnetic layer ($K_{FM}t_{FM}\sin^2\beta$) and antiferromagnetic ($K_{AFM}t_{AFM}\sin^2\alpha$) where *H*, *M*, *K*, and *t* are the applied external field, the magnetization, the anisotropy constant, and the thickness of layer, respectively. β, α and θ are the angles of the M_{FM}, M_{AFM} ,and H with respect to the easy axis [9]. $|J|$ is the antiferromagnetic coupling constant between ferromagnetic and antiferromagnetic layers.

3.2.1 Coercivity

In order to investigation of magnetic properties, we will observe hysteresis loop of ferromagnetic/ antiferromagnetic layers by calculated coercivity. The coercivity can be determined by energy of the structure for switching state condition ($H=H_c$). The coercivity depends on the magnetic state parameter β, α and θ. Substitute the angle for initial state (0^o) and reversal state (180^o) into β, α, and θ, we get H_{c1}, H_{c2} ,and H_{c3} as shown in Table 2.

Table 2. Coercivity depent on the magnetic state parameter β, α, and θ

Analytical solutions	θ	β	α
$H_{c1} = -\frac{2K_{FM}}{M_{FM}}\left[1-\frac{\lvert J\rvert(K_{AFM}t_{AFM}/K_{FM}t_{FM})}{2K_{AFM}t_{AFM}-\lvert J\rvert}\right]$	0°	0°	0°
$H_{c2} = \lvert -H_{c1}\rvert = \frac{2K_{FM}}{M_{FM}}\left[1-\frac{\lvert J\rvert(K_{AFM}t_{AFM}/K_{FM}t_{FM})}{2K_{AFM}t_{AFM}-\lvert J\rvert}\right]$	0°	180°	180°
$H_{c3} = \frac{2K_{FM}}{M_{FM}}\left[1+\frac{\lvert J\rvert(K_{AFM}t_{AFM}/K_{FM}t_{FM})}{2K_{AFM}t_{AFM}-\lvert J\rvert}\right]$	0°	180°	0°

3.2.2 Positive exchange bias field

The positive exchange bias field (H_{ex}) is the loop-shift range, it can given by Eq. (1)

$$H_{ex} \cong \frac{\lvert J\rvert}{M_{AFM}t_{AFM}} ;\ \lvert J\rvert << 2K_{AFM}t_{AFM} \qquad (1)$$

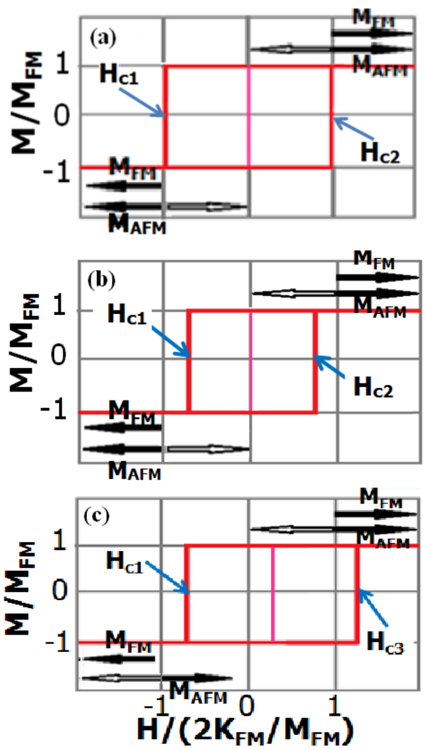


Fig. 4. Schematic of hysteresis loop respect for coercivity at three typical conditions: (a) noncoupling, (b) strong antiferromagnetic coupling ($\lvert J\rvert > 2K_{AFM}t_{AFM}$) and (c) weak antiferromagnetic coupling ($\lvert J\rvert < 2K_{AFM}t_{AFM}$)

Fig. 4. (c) seems to suggest that only weak antiferromagnetic coupling that could be performed positive exchange bias. M_{AFM} does not rotate to the reversed direction to negative following H-field and M_{FM}. When H-field is applied to positive, M_{FM} is hard to rotate with H-field due to weak antiferromagnetic coupling.

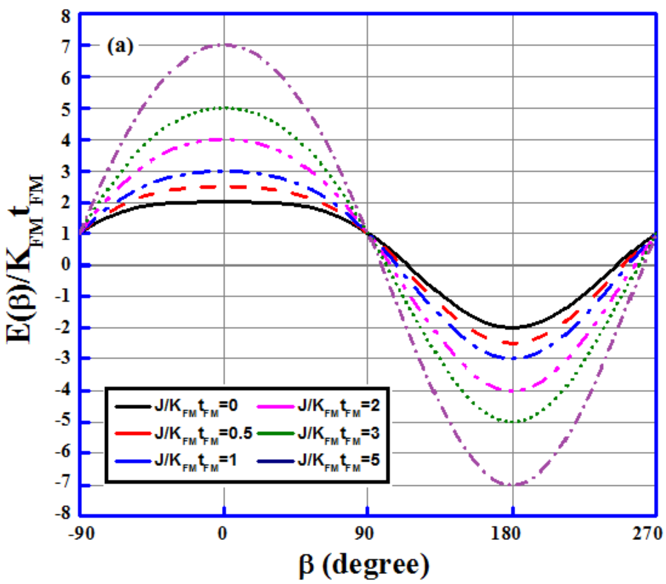
3.2.3 Energy barrier height

The energy barrier height indiscriminate the applied field is determined as $E_B = E_{MAX} - E_{MIN}$ where E_{MAX}, E_{MIN} are the maximum and minimum energy of the structure. It can be obtained as

$$E_{B,initial} = K_{FM} t_{FM} \left[1 - \frac{|J|}{2K_{FM} t_{FM}} \right]^2 \text{ for } \beta \text{ from } 0^o \text{ (initial) to } 180^o \text{ (reversal)} \quad (2)$$

$$E_{B,reverse} = K_{FM} t_{FM} \left[1 + \frac{|J|}{2K_{FM} t_{FM}} \right]^2 \text{ for } \beta \text{ from } 180^o \text{ (reversal) to } 0^o \text{ (initial)} \quad (3)$$

The energy barrier of Eq. (2)-(3) can plot in Fig. 5 (a)-(b), respectively. It suggests that the energy barrier height increases with increasing coupling constant. From the physical point of view, the energy barrier is the key issue in controlling the moment reversal properties of positive exchange bias.



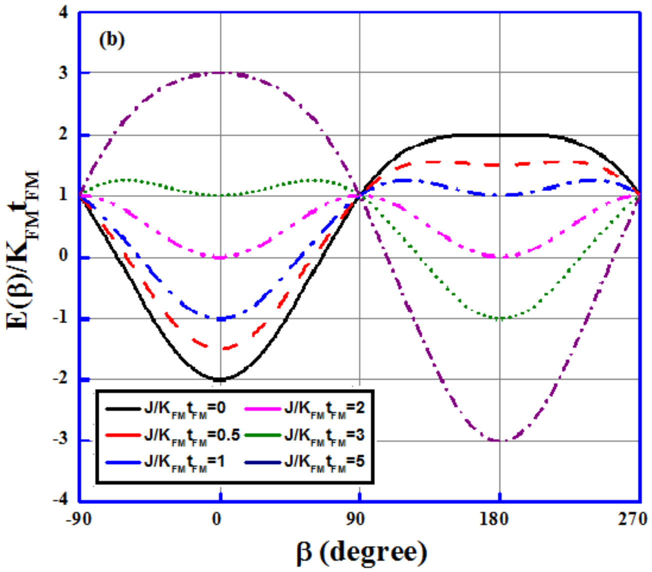


Fig. 5. Energy barrier of (a) initial to reversal state and (b) reversal to initial state

4. Conclusions

The magnetic properties of bilayer magnetic thin films are investigated in this paper. The antiferromagnetic coupling in the interface of ferromagnetic/ferrimagnetic can cause the negative coercivity. The antiferromagnetic coupling of bilayer magnetic thin films is lower than trilayer. In additional, the positive exchange bias is in the ferromagnetic/antiferromagnetic layers with weak antiferromagnetic coupling. The results of this paper offer useful information for the development of magnetic thin film with using magnetic coupling application.

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