

## Coercivity enhancement near blocking temperature in exchange biased Fe/Fe<sub>x</sub>Mn<sub>1-x</sub> films on Cu(001)

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Exchange bias is found in the Fe/Fe<sub>x</sub>Mn<sub>1-x</sub>/Cu(001) bilayer films. The coercivity  $H_c$  is enhanced at blocking temperature  $T_b$  for the films with composition  $x$  between 0.25 and 0.35, but not for those between 0.1 and 0.25. A simple model based on the discrepancy of the Néel temperature  $T_N$  and  $T_b$  is proposed, which may reveal the physical origins of these two temperature points. © 2004 American Institute of Physics. [DOI: 10.1063/1.1652415]

Exchange bias is a unidirectional anisotropy, which is found at the interface between ferromagnetic (FM) and anti-ferromagnetic (AF) materials.<sup>1</sup> It has been applied in magnetic sensors and magnetic data storage as magnetoresistive materials with a spin-valve structure.<sup>2</sup> Two significant phenomena observed in an exchange biased system are the shift of magnetic hysteresis loop along the field axis, exchange bias  $H_{ex}$ , and the increase of the loop width, coercivity  $H_c$  enhancement. The  $H_c$  is usually found to reach the maximum when the exchange bias  $H_{ex}$  is zero,<sup>2,3</sup> e.g.,  $H_c$  reaches the maximum at  $T_b$ . However, this  $H_c$  enhancement at  $T_b$  does not occur in all exchange biased systems.<sup>2,4</sup> Models accounted for the exchange biased system are, e.g., the random-field associated with the imperfect interface, the domain of AF layer, spin-flop model, etc.<sup>4-6</sup> Although a full understanding for the exchange bias is not available, the  $H_{ex}$  and  $H_c$  are affected by interfacial roughness or frustration, cooling field, domain walls in the FM or AF materials in some degree of agreement.<sup>7</sup>

In bilayer ultrathin films of 15 ML monolayer Fe/17 ML Fe<sub>x</sub>Mn<sub>1-x</sub>/Cu(001), the Fe overlayer exhibits various magnetic properties depending on the composition  $x$ .<sup>8</sup> For the films with  $x$  above 0.35, the Fe overlayer is face-centered-cubic structure and no magneto-optical Kerr effect (MOKE) signal is observed in the temperature ranging from 110 K to 330 K under the field of 1200 Oe. For the  $x$  below 0.35, the Fe overlayer is body-centered-cubic structure, which is categorized into three regimes: (a)  $x < 0.1$ , FM without exchange bias, (b)  $0.1 < x < 0.25$ , FM with exchange bias whose  $H_c$  decreases monotonically along with the increase of the temperature, and (c)  $0.25 < x < 0.35$ , FM with exchange bias whose  $H_c$  enhances at  $T_b$ . In this paper, we focus on the films with exchange bias and propose a partial coherent model to interpret this phenomena by the discrepancy between  $T_N$  and  $T_b$ .

The experiment was performed in an ultrahigh vacuum chamber with a base pressure below  $2 \times 10^{-10}$  mbar. The surface of the substrate Cu(001) was cleaned by Ar<sup>+</sup> sputtering and examined by Auger electron spectroscopy (AES)

for the cleanliness. The crystalline structure was rebuilt by annealing and checked by low energy electron diffraction for the sharp  $1 \times 1$  pattern. The films were prepared by codeposition of Fe (99.995%, at. %) and Mn (99.95%, at. %) on Cu(001) at 300 K and followed by deposition of Fe at 150 K. The composition  $x$  of the Fe<sub>x</sub>Mn<sub>1-x</sub> alloy films was adjusted by the individual deposition rate of Fe and Mn monitored by medium energy electron diffraction and calibrated by AES. The films were cooled from 300 K to 90 K with a magnetic field of 350 Oe and measured by *in situ* MOKE both at in-plane and out-of-plane orientation at the temperature increasing from 110 K to 330 K. For details of the experiments, see Refs. 9–11.

The temperature dependence of the  $H_c$  and  $H_{ex}$  for these films is shown in Fig. 1. For the films in regimes, (b) and (c), the  $H_{ex}$  decreases along with the increase of the temperature and  $T_b$  are found to be about 270 K. The significant difference is the temperature-dependent  $H_c$  behavior. For the Fe film grown on Fe<sub>x</sub>Mn<sub>1-x</sub> with  $x=0.2$ , the  $H_c$  decreases monotonically along with the increase of the temperature. For the Fe film grown on Fe<sub>x</sub>Mn<sub>1-x</sub> with  $x=0.3$ , the  $H_c$  decreases but is strongly enhanced while the  $H_{ex}$  approaches zero.

The coherent rotation model accounts for the fact that the exchange bias arises from the AF layer, which “pins” the

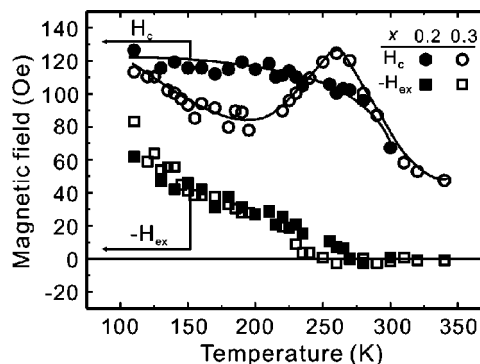


FIG. 1.  $H_{ex}$  and  $H_c$  as a function of temperature for 15 ML Fe/17 ML Fe<sub>x</sub>Mn<sub>1-x</sub>/Cu(001) with  $x=0.2$  and  $0.3$ . The  $T_b$  is about 270 K. For the films with  $x=0.2$ , the  $H_c$  decreases monotonically along with the temperature. For the films with  $x=0.3$ , the  $H_c$  reaches the maximum at  $T_b$ . The lines are guides for the eyes.

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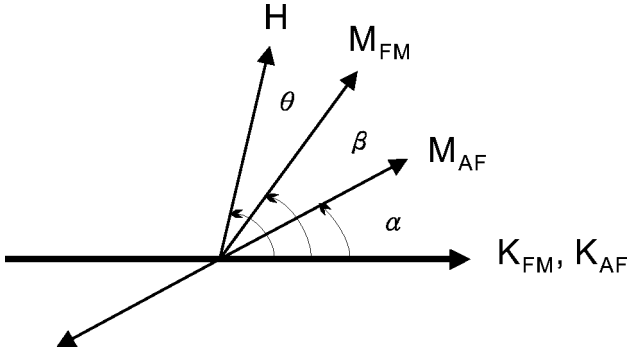


FIG. 2. Schematic illustration for the spatial relation among external field  $H$ , magnetization ( $M_{FM}$  and  $M_{AF}$ ), and anisotropy ( $K_{FM}$  and  $K_{AF}$ ) of FM and AF layers in an exchange bias system.

magnetization of the FM layer after field cooling.<sup>2,12,13</sup> The energy per unit area is written as<sup>1,2</sup>

$$E = -HM_{FM}t_{FM} \cos(\theta - \beta) + K_{FM}t_{FM} \sin^2 \beta + K_{AF}t_{AF} \sin^2 \alpha - J \cos(\beta - \alpha), \quad (1)$$

where  $H$  is the applied field,  $M_{FM}$  the saturated magnetization,  $t_{FM}$  the thickness of the FM layer,  $t_{AF}$  the thickness of the AF layer,  $K_{AF}$  the anisotropy of the AF layer, and  $J$  the interface coupling constant.  $\beta$ ,  $\alpha$ , and  $\theta$  are the angles between the magnetization and the FM anisotropy axis, the AF sublattice magnetization  $M_{AF}$  and the AF anisotropy axis, and the applied field  $H$  and the FM anisotropy axis, respectively (see Fig. 2). For simplicity,  $\theta$  is set to be zero so that the external field is applied along the easy axis of the FM layer. The hysteresis loop is obtained by minimizing the energy with respect to the angles  $\alpha$  and  $\beta$ .

For understanding the origin of the loop shift  $H_{ex}$ , a hard AF approximation is introduced that assumes the spins in AF layer are completely fixed during the rotation of the magnetic moments in the FM layer, i.e., setting  $\alpha$  to be constant (e.g., zero). The  $H_c$  and  $H_{ex}$  can be obtained as

$$E = -HM_{FM}t_{FM} \cos \beta + K_{FM}t_{FM} \sin^2 \beta - J \cos \beta, \quad (2)$$

$$H_c = \frac{2K_{FM}t_{FM}}{M_{FM}t_{FM}},$$

$$H_{ex} = -\frac{J}{M_{FM}t_{FM}}. \quad (3)$$

The exchange bias is ascribed to the interlayer coupling  $J$  between FM and AF layers. The  $H_c$  remains the same as that without exchange bias coupling.

In order to understand the origin of the  $H_c$  enhancement, a soft AF approximation is introduced by assuming the spins in the AF layer rotate with the spins in the FM layer coherently, i.e.,  $\alpha$  is set to be as  $\beta$ . The  $H_c$  and  $H_{ex}$  can be obtained as

$$E = -HM_{FM}t_{FM} \cos \beta + (K_{FM}t_{FM} + K_{AF}t_{AF}) \sin^2 \beta - J, \quad (4)$$

$$H_c = \frac{2(K_{FM}t_{FM} + K_{AF}t_{AF})}{M_{FM}t_{FM}},$$

$$H_{ex} = 0. \quad (5)$$

The  $H_c$  is enhanced by  $2(K_{AF}t_{AF})/M_{FM}t_{FM}$ . Real exchange biased systems would be in between the hard and soft AF approximation.

In this model,  $H_{ex}$  originates from the interlayer exchange coupling,  $J \cos(\beta - \alpha)$ . It disappears when  $J$  is zero or  $\alpha = \beta$ , i.e., spin decouples at FM/AF interface or the AF spins rotate completely with FM spins. The  $H_c$  enhancement is ascribed to the AF spins rotating coherently with the FM spins. Thus the more coherent-rotated spins in the AF layer, the larger  $H_c$  enhancement.

Here we propose a partial coherent model that assumes that a ratio  $\epsilon$  ( $< 1$ ) of the spins rotates coherently, i.e., assuming  $\epsilon$  ratio of the AF spins aligning along  $\beta$  and the ratio  $\kappa$  remains along  $\alpha$ . Additionally, the interlayer exchange coupling becomes smaller. Equation (1) is modified as

$$E = -HM_{FM}t_{FM} \cos(\theta - \beta) + K_{FM}t_{FM} \sin^2 \beta + \kappa K_{AF}t_{AF} \sin^2 \alpha + \epsilon K_{AF}t_{AF} \sin^2 \beta - J' \cos(\beta - \alpha), \quad (6)$$

where

$$\kappa, \epsilon < 1,$$

$$J' \propto (1 - \epsilon)J.$$

The  $H_{ex}$  and  $H_c$  are obtained as

$$H_c = \frac{2K_{FM}t_{FM}}{M_{FM}t_{FM}} + \epsilon \frac{2K_{AF}t_{AF}}{M_{FM}t_{FM}}, \quad (7)$$

$$H_{ex} = -\frac{J'}{M_{FM}t_{FM}}.$$

The temperature is an indication of the thermal fluctuation that reduces the exchange coupling between the spins in the FM, AF, and the interlayer exchange coupling at the FM/AF interface. It is reasonable to assume that more spins in AF layer are “dragged” by the spins in FM layer at higher temperature but they decouple above  $T_b$ . Therefore temperature effect is introduced in  $\epsilon$ , which increases with the temperature until  $T_b$  is reached. For  $J'$ , it decreases with the increase of the temperature and approaches zero at  $T_b$ . By setting  $h_0$  as  $2K_{FM}t_{FM}/M_{FM}t_{FM}$ ,  $h_k$  as  $2K_{AF}t_{AF}/M_{FM}t_{FM}$ , and  $j'(T)$  as  $J'(T)/M_{FM}t_{FM}$ , Eq. (7) is modified as

$$h_c = h_0 + \epsilon(T)h_k,$$

$$h_{ex} = -j'(T),$$

$$\text{set } t \equiv \frac{T}{T_c}, \quad t_b \equiv \frac{T_b}{T_c}, \quad t_N \equiv \frac{T_N}{T_c},$$

$$\Rightarrow h_0 = (1 - t)^a, \quad (8)$$

$$\epsilon(t) = \begin{cases} \left(\frac{t}{t_N}\right)^b, & t < t_b \\ \left(\frac{t_b}{t_N}\right)^b [1 - (t - t_b)]^a, & t \geq t_b \end{cases},$$

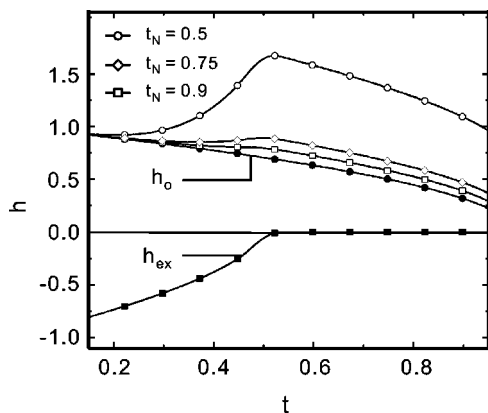


FIG. 3. Numerical results of the partial coherent model. The curves shown are deduced from the setting of  $a$ ,  $b$ , and  $c$  which are 0.5, 4, and 0.6, respectively, and  $t_b$  is set to be 0.5. The increase of  $h_c$  near  $t_b$  is more obvious in the curve with  $t_N$  closer to  $t_b$ .

$$j'(t) = \begin{cases} \left(1 - \frac{t}{t_b}\right)^c, & t < t_b \\ 0, & t \geq t_b \end{cases}$$

where  $a$ ,  $b$ , and  $c$  are positive real numbers.

The function of the temperature governing the spin coupling is formulated in the form of Curie-Weiss law,<sup>14,15</sup> which may need further modification.

A numerical result of this model is plotted in Fig. 3. For the curve with  $t_N$  equals to  $t_b$ , the increase of  $h_c$  near  $t_b$  is the largest (see the curve for  $t_N=0.5$  in Fig. 3). For the curve with  $t_N$  much larger than  $t_b$ , this increase is insignificant (see the curve for  $t_N=0.9$  in Fig. 3). In Fig. 1, the  $T_b$  for both films are close that 275 K for the film with  $x=0.2$  and 270 K for the film with  $x=0.3$ . From this model, the  $T_N$  of 17 ML  $\text{Fe}_x\text{Mn}_{1-x}$  for the  $x=0.2$  would be higher than that for the

$x=0.3$ , which agrees with the  $T_N$  for bulk  $\text{Fe}_x\text{Mn}_{1-x}$  [ $T_{N0.2}=425$  K and  $T_{N0.3}=375$  K (Ref. 16)]. Note that the  $T_N$  for the  $\text{Fe}_x\text{Mn}_{1-x}$  film is reduced by the finite size effect. The parameters such as  $a$ ,  $b$ , and  $c$  require a more detailed analysis on the temperature dependence in  $H_c$  and  $H_{ex}$  to obtain these quantities.

The exchange biased system with or without this increase of  $H_c$  at  $T_b$  might indicate the different effect of the thermal fluctuation on spin coupling in the AF layer and at the FM/AF interface.

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