Coercivity enhancement near blocking temperature in exchange biased Fe/Fe_xMn_{1-x} films on Cu(001)

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Exchange bias is found in the Fe/Fe_xMn_{1-x}/Cu(001) bilayer films. The coercivity (H_c) is enhanced at blocking temperature (T_b) for $0.25 < x < 0.35$, but not for $0.1 < x < 0.25$. 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.

Exchange bias is a unidirectional anisotropy, which is found at the interface between ferromagnetic (FM) and antiferromagnetic (AF) materials[1]. It has been applied in magnetic sensors and magnetic data storage as magneto-resistive materials with a spin-valve structure[2]. 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, which is usually found to reach the maximum when the bias field H_{ex} is zero[2,4], *e.g.* H_c reaches maximum at the T_b where H_{ex} is zero. However, this H_c enhancement at T_b does not occur in all exchange biased systems[2,4]. 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, and *etc*[1,14–16]. 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[3].

In bilayer ultrathin films of 15 ML Fe/17 ML Fe_xMn_{1-x}/Cu(001), the Fe overlayer exhibits various magnetic properties depending on the composition x[5]. For the films with x above 0.35, the Fe overlayer is face-centered cubic structure and no 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: (I) $x < 0.1$, FM without exchange bias, (II) $0.1 < x < 0.25$, FM with exchange bias, whose H_c decreases monotonically along with the increase of the temperature, and (III) $0.25 < x < 0.35$, FM with exchange bias, whose H_c enhances at T_b. In this article, 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, which might indicate the different physical origins of the temperature points.

The experiment was performed in an ultra high vacuum (UHV) chamber with a base pressure below 2×10^{-10} mbar. The surface of the substrate Cu(001) was cleaned by Ar^+ 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 (LEED) for the sharp 1×1 pattern. The films were prepared by co-deposition 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_xMn_{1-x} alloy films was adjusted by the individual deposition rate of Fe and Mn monitored by medium energy electron diffraction (MEED) and calibrated by AES. The films were cooled from 300 K to 90 K with an magnetic field of 350 Oe and measured by *in situ* magneto-optical Kerr effect (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 Ref.[6,7].

The temperature dependence of the H_c and H_{ex} for these films are shown in the Fig. 1. For the films in regime (II) and (III), 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_xMn_{1-x} with $x = 0.2$, the H_c decreases monotonically along with the increase of the temperature. For the Fe film grown on Fe_xMn_{1-x} with $x = 0.3$, the H_c decreases but is strongly enhanced while the H_{ex} approaches zero.

The coherent rotation model accounts that the exchange bias arises from the AF layer, which "pins" the magnetization of the FM layer after field cooling[2,11]. The energy per unit area is written as[1,2]

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

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. β, α, and θ 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, θ is set to be zero 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 angle α and β.

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 α to be constant (*e.g.* zero). The H_c and H_{ex} can be obtained.

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

$$
\begin{aligned}
H_c &= \frac{2K_{FM}t_{FM}}{M_{FM}t_{FM}} \\
H_{ex} &= -\frac{J}{M_{FM}t_{FM}}
\end{aligned} \tag{3}
$$

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.* α is set to be as β. The H_c and H_{ex} can be obtained.

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

$$
\begin{aligned}
H_c &= \frac{2(K_{FM}t_{FM} + K_{AF}t_{AF})}{M_{FM}t_{FM}} \\
H_{ex} &= 0
\end{aligned} \tag{5}
$$

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 decoupled at FM/AF interface or the AF spins rotate completely with FM spins, respectively. The H_c enhancement is ascribed to the AF spins rotates coherently with the FM spins. Thus the more coherent-rotated spins in the AF layer, the larger H_c enhancement.

Here we propose a model that assumes that a ratio ϵ ($<$1) of the spins rotates coherently, *i.e.* ϵ ratio of the AF spins aligning along β and the ratio κ remains along α. Additionally, the interlayer exchange coupling becomes smaller. Eq. 1 is modified as:

$$
\begin{aligned}
E = &- HM_{FM}t_{FM}\cos(\theta-\beta) + K_{FM}t_{FM}\sin^2\beta \\
&+ \kappa K_{AF}t_{AF}\sin^2\alpha + \epsilon K_{AF}t_{AF}\sin^2\beta \\
&- J'\cos(\beta-\alpha) \\
where& \\
&\kappa, \epsilon < 1 \\
&J' \propto (1-\epsilon)J
\end{aligned} \tag{6}
$$

The H_{ex} and H_c are obtained as:

$$
\begin{aligned}
H_c &= \frac{2K_{FM}t_{FM}}{M_{FM}t_{FM}} + \epsilon\frac{2K_{AF}t_{AF}}{M_{FM}t_{FM}} \\
H_{ex} &= -\frac{J'}{M_{FM}t_{FM}}
\end{aligned} \tag{7}
$$

Temperature is as 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 decoupled above T_b. Therefore temperature effect is introduced in ϵ, which would increase with the temperature until T_b. For J', it would decrease 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:

$$
\begin{aligned}
&h_c = h_0 + \epsilon(T)h_k \\
&h_{ex} = -j'(T) \\
set \quad & t \equiv \frac{T}{T_c}, \qquad t_b \equiv \frac{T_b}{T_c}, \qquad t_N \equiv \frac{T_N}{T_c} \\
\Longrightarrow \quad & h_0 = (1-t)^a \\
&\epsilon(t) = \begin{cases} (\frac{t}{t_N})^b, & t < t_b \\ (\frac{t_b}{t_N})^b(1-(t-t_b))^a, & t \geq t_b \end{cases} \\
&j'(t) = \begin{cases} (1-\frac{t}{t_b})^c, & t < t_b \\ 0, & t \geq t_b \end{cases}
\end{aligned} \tag{8}
$$

where a, b, and c are positive real number.

The function of the temperature governing the spin coupling is formulated in the form of Curie-Weiss law[13], 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 Fe_xMn_{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 Fe_xMn_{1-x} ($T_{N0.2}$ = 425 K and $T_{N0.3}$ = 375 K[9]). Note that the T_N for the Fe_xMn_{1-x} film is reduced by the finite size effect. The parameters such as a, b, and c require more detail analysis on the temperature dependence in H_c and H_{ex} to obtain these quantities.

For 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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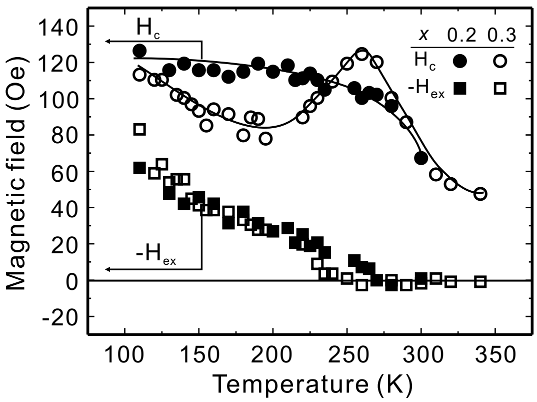

FIG. 1: H_{ex} and H_c as a function of temperature for 15 ML Fe/17 ML Fe_xMn_{1-x}/Cu(001) with $x = 0.2$ and 0.3. The T_b is about 270 K. For the films with $x = 0.2$, the H_c decreases monotonically along with the temperature. For the films with $x = 0.3$, the H_c reaches the maximum at T_b. The lines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

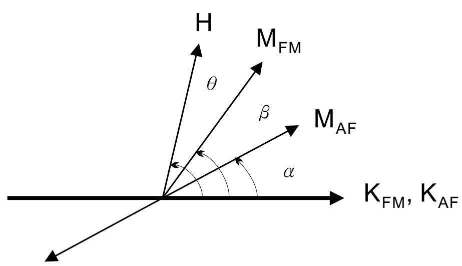

FIG. 2: Schematic illustration for the spatial relation among external field (H), magnetization (M_{FM} and M_{AF}) and anisotropy (K_{FM} and K_{AF}) of FM and AF layers in an exchange bias system.

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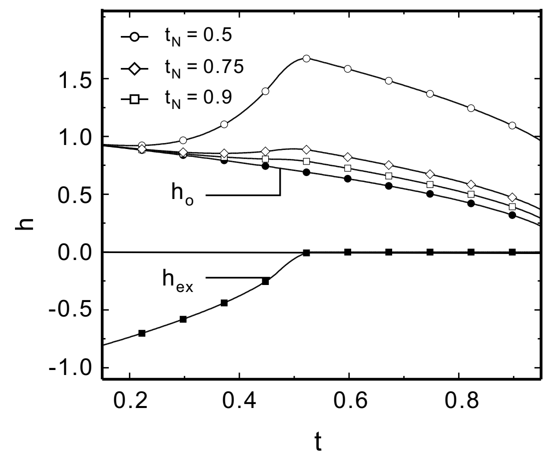

FIG. 3: Numerical results of the partial coherent model. The curves shown are deduced from the setting of a, b, and c are 0.5, 4, and 0.6, respectively, and t_b is set to be 0.5. The increase of h_c near t_b is more obvious in the curve with t_N closer to t_b.

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