90° Magnetization Switching in Thin Fe Films Grown on Stepped Cr(001)

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The ferromagnetic/antiferromagnetic interfacial interaction was investigated in thin Fe films grown on stepped Cr(001) with the steps parallel to the [100] direction. Above the Néel temperature of the Cr, the atomic steps induce a uniaxial magnetic anisotropy with the easy axis parallel to the step edges. Below the Néel temperature, the Fe-Cr interfacial interaction favors the Fe magnetization perpendicular to the step edges. The competition between the Fe-Cr interaction and the step-induced magnetic anisotropy results in an in-plane 90° magnetization switching from perpendicular to the step edges at low step-density to parallel to the step edges at high step density. [S0031-9007(98)07012-4]

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Investigations on the magnetic exchange bias have generated great interest in the study of the magnetic interaction between ferromagnetic (F) and antiferromagnetic (AF) thin films. There are two types of F/AF interfaces: uncompensated and compensated, corresponding to the nonzero and zero net magnetic moments at the AF surface, respectively. After the original work of Meiklejohn and Bean [1], research was focused for many years on the uncompensated type which was believed to be responsible for the exchange bias. However, the recent discovery of the exchange bias in the $Fe/FeF_2(110)$ system [2], where the $FeF_2(110)$ surface is a compensated AF surface, prompted a reevaluation of the physical picture of the F/AF interaction in compensated systems. The difficulty in understanding the F/AF compensated systems comes from the fact that the competition between the intralayer magnetic interaction and the F/AF interfacial interaction leads to magnetic frustration, where not all the nearest-neighbor spins can be in their local minimum energy configurations. Therefore, the first important issue in compensated systems was the following: *What is the ground state spin configuration as a result of the magnetic frustration?* In a recent theoretical simulation, Koon [3] showed that the magnetic frustration in a compensated system could result in 90° coupling between the F and AF magnetic moments at the interface although the F/AF interfacial interaction itself has a collinear form. This prediction is supported by several recent experiments [4]. However, the physical origin of this 90° coupling, such as its relation to the frustration, remains obscure. One experimental approach to address this issue is to control the magnetic frustration using atomic steps on an uncompensated AF surface. Evidence of this step-induced magnetic frustration was found in the Fe/Cr(001) system where the uncompensated Cr(001) surface [5] can be partially compensated by the presence of random steps [6] in the transverse spin density wave (SDW) regime ($120 < T < 311$ K). The magnetic behavior resulting from this kind of frustration is believed to depend critically on the terrace length of the atomic steps [7]. Therefore, a study of the magnetic phases with different degrees of step-induced frustration will provide information on the origin of the 90° coupling in the compensated F/AF systems. In this Letter, we report on the study of Fe films grown on a stepped Cr(001) surface. We found that the Fe-Cr interfacial frustration favors the Fe magnetization perpendicular to the step edges. In competing with the step-induced magnetic anisotropy, which favors the magnetization parallel to the step edges, the Fe magnetization undergoes an in-plane 90° switching from perpendicular to the step edges at low step density to parallel to the step edges at high step density.

A Cr(001) single crystal disk of 2 mm thickness and 10 mm diameter was mechanically polished with 0.25 μm diamond paste finish. Half of the crystal was kept in the (001) orientation while the other half was polished into a curved shape with step edges parallel to the [100] crystallographic direction. The curved shape provided a continuous range of the vicinal angle (α) from 0° to 10°. The substrate was cleaned with cycles of Ar ion sputtering and annealing in an ultrahigh vacuum chamber with a base pressure of $\sim 5 \times 10^{-11}$ torr. Details on the Cr substrate preparation and characterization are presented elsewhere [8]. A substrate temperature of 480 K was used during the Fe film growth to achieve a smooth film surface without the substrate-overlayer intermixing [6]. Hysteresis loops were obtained by *in situ* surface magneto-optic Kerr effect (SMOKE) measurements in the longitudinal configuration with a He-Ne laser as the light source. For all films studied, no polar loops were observed so that the Fe magnetization always remains in the film plane. For measurements on stepped surfaces, the reflection angle of the SMOKE laser beam was used to determine the local vicinal angle. A slit was used on the path of the reflection beam to improve the vicinal angular resolution to better than 0.25°.

We first investigated the Fe films grown on the flat half ($\alpha = 0$) of the Cr substrate. Wedged samples were used to provide a thickness range of 5–50 Å. At $T = 480$ K, which is well above the Néel temperature (T_N) of Cr (311 K), the hysteresis loops of the Fe films exhibit a square shape with full remanence for all thicknesses. Below the T_N, the remanence of the loops remains 100%

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for thicker films (>35 Å), but is reduced for thinner films (Fig. 1). This remanence reduction has been attributed to the competition between the Fe-Fe and Fe-Cr interactions in the presence of random atomic steps on the Cr surface [6]. For thicker Fe films, the Fe-Fe interaction dominates the Fe-Cr interaction so that magnetic domains will be formed at the Fe-Cr interface to give a full remanence. For thinner Fe films, the Fe-Cr interaction dominates the Fe-Fe interaction so that magnetic domains will be formed inside the Fe film to result in a low remanence [6,7]. Since we are interested in the effect of the Fe/Cr *interfacial* frustration, we will focus our attention on the thicker Fe film regime ($d > 35$ Å). For this purpose, we studied a 40 Å Fe film on the curved side of the Cr(001).

It has been shown that atomic steps can induce an in-plane uniaxial magnetic anisotropy [9–12]. To separate the effect of the step-induced anisotropy from the Fe-Cr interfacial frustration, we first measured the magnetic hysteresis loops on the curved substrate at $T = 480$ K, well above the T_N of Cr. The square hysteresis loops for field parallel to the step edges and the split loops for field perpendicular to the step edges (Fig. 2) clearly show the existence of the step-induced uniaxial anisotropy with the easy magnetization axis parallel to the step edges. The splitting field (H_S), which is proportional to the strength of the uniaxial anisotropy (K), increases with α (Fig. 3), in agreement with previous work [9,12]. A detailed study of the α dependence of the step-induced anisotropy will be published in a subsequent work.

The sample temperature was then cooled to 140 K to turn on the Fe-Cr interaction. Figure 4 shows hysteresis loops at different vicinal angles for magnetic field parallel and perpendicular to the step edges. At high vicinal angles ($\alpha \geq 4°$), the loops exhibit the same character as the high temperature loops, indicating that the Fe magnetization is still parallel to the step edges. At low vicinal angles ($\alpha \leq 3°$), however, the loops clearly show a 90° switching of the magnetization from a parallel to a perpendicular direction to the step edges. This result implies that the Fe/Cr interfacial frustration favors the Fe magnetization perpendicular to the step edges. Then the interesting question is as follows: Why does this 90° switching not occur at high vicinal angles? A simple explanation is that the Fe-Cr interfacial interaction and the step-induced magnetic anisotropy scale differently with the step density: The Fe-Cr interaction scales as the terrace length (L), and the step-induced anisotropy scales as the step density ($1/L$). Therefore, the Fe-Cr interaction should dominate the step-induced anisotropy at low step density to align the Fe magnetization perpendicular to the step edges, and the step-induced anisotropy should dominate the Fe-Cr interaction at high step density to align the Fe magnetization parallel to the step edges. The role of this competition is further evidenced in the temperature dependence of hysteresis loops for fixed α. Figure 5 displays several loops for $\alpha = 2°$ and 5° at different temperatures for magnetic fields parallel to the step edges. At $\alpha = 5°$, where the step-induced anisotropy is strong enough to dominate the Fe-Cr interaction in the whole temperature range, the full-remanence easy axis character remains down to 140 K. At $\alpha = 2°$, however, the easy axis character seen at high temperature evolves into a hard axis character as the Fe-Cr interaction strength increases by lowering the temperature. The above results clearly demonstrate that this 90° switching is due to the Fe-Cr interfacial interaction.

To better understand how the atomic steps result in the observed 90° switching, we consider a model which consists of the intralayer Fe-Fe interaction, $-J_0 \sum_{ij} \vec{S}_{\mathrm{Fe},i} \cdot \vec{S}_{\mathrm{Fe},j}$, and the interfacial Fe-Cr interaction, $J_1 \sum_{ij} \vec{S}_{\mathrm{Cr},i} \cdot \vec{S}_{\mathrm{Fe},j}$ in a stepped Fe/Cr(001) system (Fig. 6). Here J_0 and J_1 are the strengths of the Fe-Fe and Fe-Cr interactions, respectively. The alternating Cr moments in adjacent steps produce a periodic Fe-Cr interaction. It has been shown that the Cr moments are in the film plane in the Fe/Cr(001)

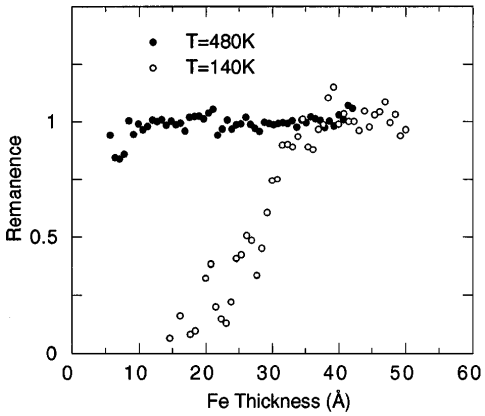

FIG. 1. SMOKE measurements of remanence as a function of Fe film thickness for Fe wedges grown on flat Cr(001). The remanence has been normalized to the film thickness.

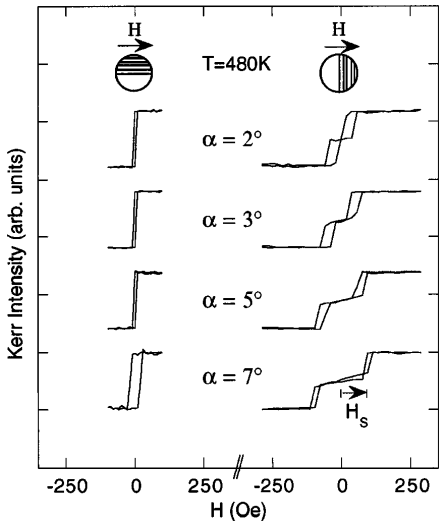

FIG. 2. SMOKE loops measured at 480 K for a 40 Å Fe film grown on a *curved* Cr(001) at different vicinal angles (α). The splitting of the loops for field perpendicular to the step edges is due to the step-induced uniaxial magnetic anisotropy with the easy axis parallel to the step edges.

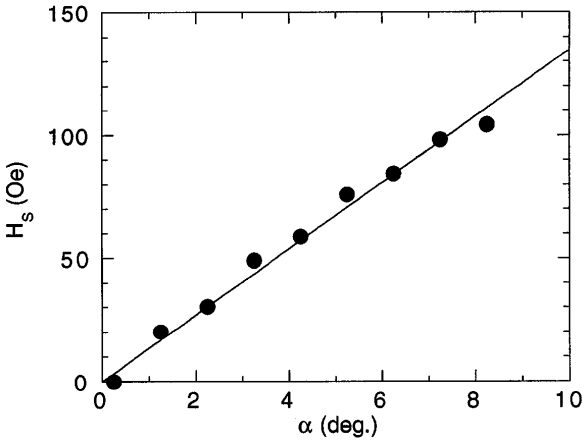

FIG. 3. Splitting field (H_S) in Fig. 2 as a function of vicinal angle α. The solid line is a guide to the eyes.

system [6,13]. For in-plane spin, the spin direction can only be parallel or perpendicular to the step edges due to symmetry considerations. Without knowing the sign of the step-induced uniaxial magnetic anisotropy for the Cr, we have assumed that the Cr moments are parallel to the step edges, as the Fe was at high temperature. Verification of this assumption requires future experiments using other techniques. Taking the Fourier component of this interaction, $J_{1k}\sin(kx)$, with $k = n\pi/L$, the Fourier component of the Fe film energy per unit length is

$$E_k = \frac{1}{2L}\int_0^{2L}\frac{dx}{a}\left\{-J_{1k}\sin(kx)\sin\theta(x,0) + J_0 a\int_0^d dz[(\partial_x\theta)^2 + (\partial_z\theta)^2]\right\}. \quad (1)$$

Here d is the Fe film thickness, a is the lattice constant, and $\theta(x,z)$ is the angular variation of the Fe moments (we assume that the Fe moments vary only in the film plane and are independent of the y coordinate). One can immediately realize that Eq. (1) is similar to the form used by Slonczewski in explaining the biquadratic coupling [14] as long as the periodic interlayer coupling in Slonczewski's model is replaced by our periodic Fe-Cr interfacial interaction. Then, Eq. (1) is expected to result in an Fe magnetization perpendicular to the step edges plus a small fluctuation in θ. Indeed, using a step function for the interfacial coupling, $J_1(x) = J_1\,\mathrm{sgn}[\sin(\pi x/L)]$, the total energy per unit length can be minimized to give

$$\theta_k = \bar{\theta} - \frac{J_{1k}\sin(kx)\cos\bar{\theta}\cosh k(d-z)}{2J_0 ak\sinh(kd)}, \quad (2)$$

$$E = -\frac{2J_1^2}{J_0}\frac{L}{a^2}\sum_{m=1}^{\infty}\frac{\coth[(2m-1)\pi d/L)]}{\pi^3(2m-1)^3}\cos^2\bar{\theta} \approx -\frac{2J_1^2 L\coth(\pi d/L)}{J_0\pi^3 a^2}\cos^2\bar{\theta}. \quad (3)$$

Equation (3) favors the Fe magnetization perpendicular to the step edges ($\bar{\theta} = 0$). This energy has to compete with the step-induced magnetic anisotropy energy, $(K/L)\cos^2\bar{\theta}$, which favors the Fe magnetization parallel to the step edges. Thus, a 90° switching of the Fe magnetization will occur at

$$\frac{K}{L} = \frac{2J_1^2 L\coth(\pi d/L)}{J_0\pi^3 a^2}. \quad (4)$$

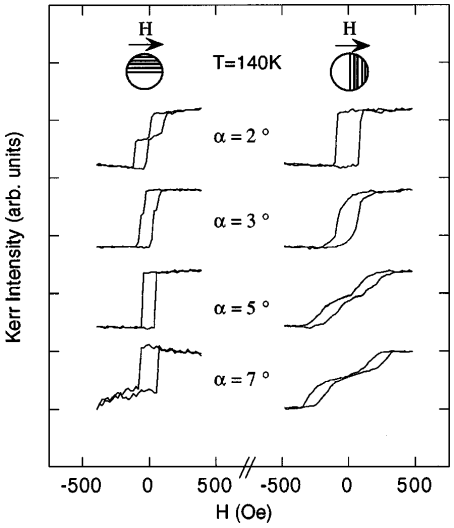

FIG. 4. SMOKE loops measured at 140 K for the 40 Å film in Fig. 2. The magnetization easy axis for $\alpha \le 3°$ switches to the direction perpendicular to the step edges.

K can be estimated from the splitting field in Fig. 3, $K/L \approx (d/a^2)\mu H_S = (d/a^2)\mu H_S^0\alpha$, where $\mu = 2.2\mu_B = 1.26\times 10^{-5}$ meV/G is the magnetic moment of the Fe and $H_S^0 = 768$ Oe/rad is the slope of Fig. 3. Then Eq. (4) gives the following condition for the 90° switching:

$$\alpha_C^2 = \frac{2J_1^2 a}{J_0\pi^3\mu H_S^0 d}\coth\left(\frac{\pi d\alpha_C}{a}\right). \quad (5)$$

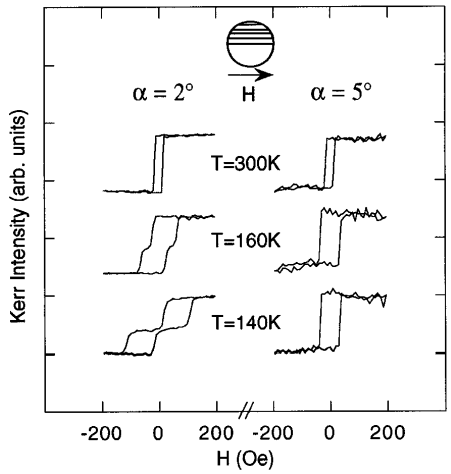

FIG. 5. Temperature dependence of SMOKE loops for $\alpha = 2°$ and $\alpha = 5°$ with magnetic field parallel to the step edges for a 40 Å film. While the magnetization easy axis remains parallel to the step edges for all temperatures for $\alpha = 5°$, the magnetization easy axis for $\alpha = 2°$ switches by 90° as the temperature is lowered.

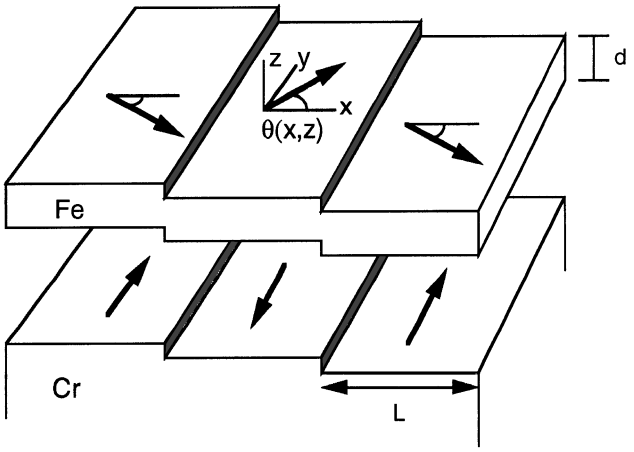

FIG. 6. Schematic drawing of Fe films on stepped Cr(001). Arrows indicate the spin directions of Fe and Cr.

Taking the value of $J_0 = 11.9$ meV [15], $a = 1.435$ Å, $d = 40$ Å, and $J_1 = 0.31$ meV [16], Eq. (5) yields the critical angle $\alpha_C \sim 2.5°$, which roughly agrees with our experiment.

It is constructive to consider the ultrathin limit ($d \ll L$), where there is no twisting of the Fe spins along the normal direction of the film, to understand the physical meaning of the 90° coupling. The twisting of Fe moments across an atomic step is equivalent to producing a θ domain wall over a length L (Fig. 6). This will cost an energy $E_1 \approx J_0\theta^2 d/L$. On the other hand, the twisting will lower the Fe-Cr interaction energy by $E_2 \approx J_1\theta L/a$. Thus, the total energy change per unit length by twisting the Fe moments is $E = (E_1 + E_2)/L = J_0\theta^2 d/L^2 - J_1\theta/a$. Minimizing this energy yields $\theta \approx J_1 L^2/(2J_0 ad)$ and $E \approx -J_1^2 L^2/(4J_0 a^2 d)$, corresponding exactly to the ultrathin limit of Eqs. (2) and (3). Therefore, the 90° coupling between the Fe and Cr originates from the angular twisting of the Fe moments. This phenomenon is also intrinsically related to the spin-flop transition in an antiferromagnet: By applying a strong enough magnetic field along the easy axis, the antiferromagnet moments switch by ~90° to be perpendicular to the magnetic field plus a small twisting to form a canted configuration. From the point of view of mean field theory, the Fe-Cr interaction $J_1 \sum_{ij} \vec{S}_{\mathrm{Cr},i} \cdot \vec{S}_{\mathrm{Fe},j}$ in the Fe/Cr system is equivalent to applying a "magnetic field" $J_1\langle\vec{S}_{\mathrm{Fe}}\rangle$ to the Cr moments at the interface, except that in this case the Cr moments are fixed and the magnetic field $J_1\langle\vec{S}_{\mathrm{Fe}}\rangle$ can rotate in space. Then, the spin-flop equivalent transition in the Fe/Cr system is to rotate the magnetic field $J_1\langle\vec{S}_{\mathrm{Fe}}\rangle$ to the perpendicular direction of the Cr moments. Therefore, it is not surprising to obtain the 90° coupling between Fe and Cr.

In the above discussions, we have ignored any spin direction change in the Cr. The Cr spins should also twist periodically by the same mechanism as the Fe spins. Koon's calculation clearly shows this configuration [3]. Another point we have not addressed is the domain wall formation inside the Cr. This situation becomes important especially when the F/AF interaction is much stronger than the AF intralayer interaction. In such a case, the spins of the F and AF at the interface will be locked together, and a parallel domain wall inside the AF will be formed in response to the rotation of the F magnetization [17]. In fact, it is thought that it is the unwinding of this domain wall that gives exchange biasing in the compensated F/AF system [3]. In the Fe/Cr(001) case, this situation does not occur because the Fe-Cr interaction is much weaker than the Cr-Cr interaction. That is probably why exchange biasing was not clearly observed in this system [6]. Another possibility for this 90° switching is that the step-induced anisotropy for the lower step density changes its sign upon cooling. However, this is unlikely because the step-induced anisotropy in other systems does not exhibit such a temperature dependence.

In summary, Fe on stepped Cr(001) was investigated in the vicinal angle range of 0°–10°. Below the Néel temperature of the Cr, we found that the Fe-Cr interfacial interaction favors the Fe magnetization perpendicular to the step edges. Its competition with the step-induced magnetic anisotropy causes the Fe magnetization to undergo a 90° switching from perpendicular to the step edges at low step density to parallel to the step edges at high step density. This phenomenon can be explained based on a model similar to the one used by Slonczewski for biquadratic coupling.

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