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Enhanced perpendicular magnetic anisotropy in Fe/Mn bilayers by incorporating ultrathin ferromagnetic underlayer through magnetic proximity effect

Bo-Yao Wang,[1] Chieh-Chen Chiu,[2] Wen-Chin Lin,[2,a)] and Minn-Tsong Lin[1,3,b)]
[1]*Department of Physics, National Taiwan University, 106 Taipei, Taiwan*
[2]*Department of Physics, National Taiwan Normal University, 116 Taipei, Taiwan*
[3]*Institute of Atomic and Molecular Sciences, Academia Sinica, Taipei, Taiwan*

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The perpendicular magnetic anisotropy(PMA) was shown to be established in ferromagnetic (FM)/fcc-Mn bilayers through the FM-antiferromagnetic (AFM) exchange coupling. We demonstrate here that such PMA can be further enhanced by incorporating an ultrathin Fe film as an underlayer. In a series of Fe/Mn bilayers, hysteresis loop measurement shows that the thickness of top Fe layer with PMA can be extended to a thicker range while an ultrathin Fe underlayer is inserted. Such enhancement of PMA is attributed to an increase of AFM ordering on the Mn film originated from the magnetic proximity effect with the Fe underlayer. © *2013 AIP Publishing LLC*. [http://dx.doi.org/10.1063/1.4816478]

As the size of the magnetic bits is reduced for magnetic devices gaining the higher storage capacity, maintaining high thermal stability of the magnetic storage layer for nonvolatility and low switching field for reasonable power consumption becomes important issues. Utilizing the perpendicular magnetic anisotropy (PMA) and spin-transfer torque (STT) effect for reading and writing the magnetic logic states in magnetic devices is expected to be path way for achieving these goals.[1–4] To stabilize the PMA of the magnetic storage layer in STT devices, current approach often applies the interface anisotropy between the ferromagnetic (FM) layer and non-magnetic layer.[3–6] A conventional way for gaining the higher thermal stability of PMA is through a fabrication of multilayer structure. However, this approach results in a thicker magnetic storage layer, which could lead to a higher STT threshold and a drawback of increasing power consumption.[3,5,7]

It has been reported recently that the antiferromagnetic (AFM) fcc-Mn thin film can lead to PMA on adjacent FM layer through the AFM-FM exchange coupling.[8–10] Although the AFM-FM exchange coupling is known to be established at interface, the strength is determined by the magnetic ordering of whole AFM layer through the finite size effect.[11] Therefore, a stable PMA could be achieved by increasing the thickness of AFM layer in the same FM/AFM bilayer, and the overall thickness required for perpendicular magnetic layer could be much reduced as compared with the current multilayer structure. However, similar to other well-known AFM-induced phenomenon like exchange bias field, the magnitude of PMA in FM/Mn bilayers is determined by the magnetic ordering of the AFM Mn layer characterized by the magnetic ordering temperature ($T_{Ordering}$). For the bulk fcc-Mn antiferromagnet, the $T_{Ordering}$ is about 540 K.[12,13] The $T_{Ordering}$ could become much lower as the thickness of fcc-Mn layer is reduced into the ultrathin regime. From the aspect of future application in perpendicular-based magnetic devices, it is important to search for an approach that can enhance the $T_{Ordering}$ of the fcc-Mn thin film. According to prior reports,[14–16] the magnetic ordering of a magnetic ultrathin film is possible to be enhanced by an another magnetic layer with the higher $T_{Ordering}$ through a direct exchange coupling, namely magnetic proximity effect. In FM/AFM bilayer, such effect is also known to enhance the $T_{Ordering}$ of AFM layer or improve the long range order for exchange bias field.[17–19] However, the influence of magnetic proximity effect on the magnetic ordering of the fcc-Mn thin film as well as the strength of the induced PMA is still unknown.

In this letter, we report that the PMA of Fe/Mn bilayer can further be enhanced by incorporating an ultrathin Fe film as an underlayer. Our hysteresis loop measurement shows that the thickness of top Fe layer with PMA can be extended to a thicker range while an ultrathin Fe underlayer is inserted. Such enhancement of PMA is attributed to an increase of AFM ordering (or $T_{Ordering}$) on the Mn film originated from the magnetic proximity effect with the Fe underlayer. This finding demonstrates a possible approach to increase the thermal stability of a low dimensional antiferromagnet for promoting the PMA.

Samples of Fe/Mn and Fe/Mn/Fe ultrathin films were prepared and investigated *in-situ* in an ultrahigh-vacuum (UHV) NTU-NSRRC Nanomagnetism Preparation Chamber with a base pressure of 2×10^{-10} Torr. The $Cu_3Au(001)$ single-crystal substrates with 0.1° miscut were cleaned by cycles of 2 keV Ar^+ ion sputtering and annealed at 765 K for 5 min and at 645 K for 30 min to obtain a well-ordered crystalline structure. The Fe and Mn thin films were deposited with thermal evaporation guns (Omicron, EFM-3) at 300 K. The growth of the thin films was monitored by medium-energy electron diffraction (MEED), in which the oscillation of specular intensity provided the information for a precise control of the film thickness.[20] The crystalline structure of films was characterized by low-energy electron diffraction (LEED) and LEED-I/V curves.[8,21] A finding of invariant

a)Electronic mail: wclin@ntnu.edu.tw
b)Electronic mail: mtlin@phys.ntu.edu.tw

structure for the top Fe layer or Mn layer upon an insertion of ultrathin Fe underlayer suggests its unconcerned relation to the variation of magnetic properties.[22] The magnetic hysteresis loops of thin films were measured on the basis of the magneto-optical Kerr effect (MOKE) in both the longitudinal and polar geometries at various temperatures.

Figure 1(a) shows the hysteresis loops of the 6 ML Fe/Mn bilayers with a variation of Mn film thickness (t_{Mn}). The magnetic anisotropy of the Fe film aligns in-plane direction as the Mn film at low coverage and then changes to out-of-plane direction as t_{Mn} was increased. This presents a phenomenon of spin-reorientation transition (SRT) from in-plane to out-of-plane direction, which is consistent with previous report.[8] On the other hand, Fig. 1(b) shows the hysteresis loops of the Fe/6 ML Mn bilayers with a variation of top Fe film thickness (t_{Fe}^{top}). Inversely, an increase of the t_{Fe}^{top} leads to change of the magnetic anisotropy from out-of-plane to in-plane direction. This SRT is attributed to an increased contribution of the in-plane oriented shape anisotropy from a thicker FM film.

For those Fe/Mn bilayers with in-plane magnetic anisotropy, however, an insertion of 1.5–2.5 ML ultrathin Fe underlayer leads to the presence of PMA, as displayed in Fig. 2(a). According to previous reports[23,24] and also our measurement, ultrathin Fe film ($t_{Fe} <\sim 3$ ML) grown on $Cu_3Au(001)$ exhibits PMA owing to interface anisotropy with substrate. However, in our measurements, 5 ML Mn/1.5–2.5 ML Fe/$Cu_3Au(001)$ films show absence of magnetic hysteresis loops even though the temperature was decreased to 190 K (not shown in figures). Such behavior could be attributed to a strong coercivity enhancement effect caused by the AFM Mn layer, which is usually significant while the thickness of FM layer in FM/AFM bilayer is decreased.[25] Thus, the hysteresis loops presented in Fig. 2(a) are concluded to be mainly contributed by the top Fe layer. To realize a general magnetic feature of the Fe/Mn bilayer upon an insertion of ultrathin Fe underlayer, we compare the magnetic hysteresis loops between Fe/Mn bilayers and Fe/Mn/2.5 ML Fe trilayers as functions of thickness for the top Fe film and Mn layer. Figures 2(b) and 2(c) display the magnetic easy axis phase diagram of the Fe/Mn bilayers and Fe/Mn/Fe trilayers, respectively. As compared with Fe/Mn bilayers, the SRT boundary of Fe/Mn/2.5 ML Fe trilayers is further shifted to the higher value of t_{Fe}^{top} by 2 ML. This indicates that an insertion of ultrathin Fe underlayer can in general lead to enhancement of PMA on the top Fe layer.

To clarify the origin behind the enhanced PMA in Fe/Mn upon an insertion of ultrathin Fe underlayer, the crystalline structure of top Fe layer and Mn layer has been examined by LEED I/V with kinetic approach.[22] Since the crystalline structure of the top Fe film and Mn layer is nearly invariant while the ultrathin Fe underlayer is inserted, its effect on the enhancement of the PMA in Fe/Mn/Fe trilayers can therefore be excluded.[22] The origin is much possible to be associated with a variation of magnetic ordering on Mn layer affected by the magnetic coupling from the Fe underlayer. To confirm this point, we compare the $T_{Ordering}$ of the Mn film in Fe/Mn bilayer and Fe/Mn/Fe trilayer. Despite a difficulty of directly measuring the $T_{Ordering}$ of an AFM ultrathin film, the "effective" $T_{Ordering}$ can in general be probed through monitoring the threshold temperature of the AFM-induced phenomenon like the enhancement of H_c in a FM/AFM bilayer.[17,18] Figure 3 shows the hysteresis loops and the corresponding H_c of the perpendicularly magnetic 6 ML Fe/4.5 Mn bilayer and 6 ML Fe/4.5 ML Mn/2.5 ML Fe trilayer as functions of temperature. In the former case, the H_c behaves only weak enhancement from 25 Oe to 50 Oe as the temperature decreases from 196 K to 186 K. For the latter case, however, the H_c is significantly enhanced by 80 times from 10 Oe to 800 Oe as the temperature decreases from 210 K to 196 K. Such a huge H_c enhancement in the latter case suggests an enhanced AFM ordering for the Mn layer incorporated with ultrathin Fe underlayer. According to the temperature-dependent H_c curves displayed in Fig. 3, the $T_{Ordering}$ of the Mn layers can be estimated. In the present

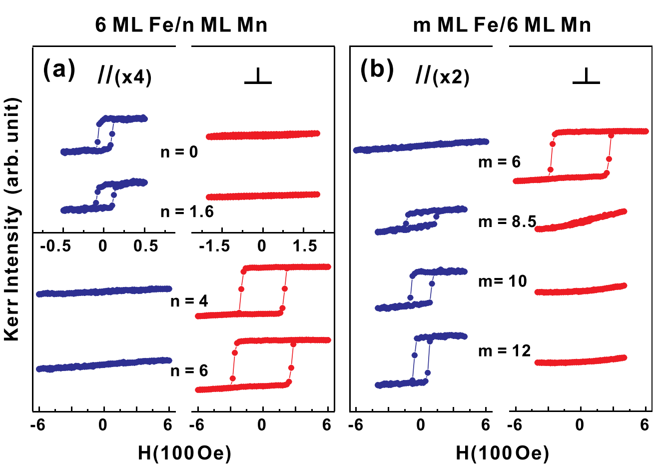

FIG. 1. Magnetic hysteresis loops of (a) 6 ML Fe/n ML Mn bilayers as a function of the Mn film thickness and (b) m ML Fe/6 ML Mn bilayers as a function of thickness of top Fe layer, measured at 195 K.

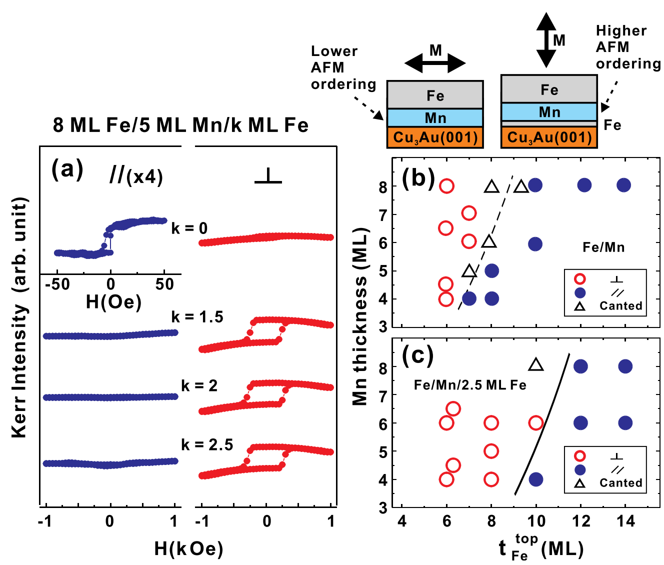

FIG. 2. (a) Magnetic hysteresis loops of 8 ML Fe/5 ML Mn/k ML Fe trilayers as a function of Fe underlayer thickness measured at 195 K. (b) and (c) Magnetic easy axis phase diagrams of Fe/Mn bilayers and Fe/Mn/2.5 ML Fe trilayers, respectively, measured at 195 K. The dashed and solid lines in (b) and (c) show the SRT boundary of the Fe/Mn and Fe/Mn/2.5 ML Fe trilayers, respectively, where the SRT boundary is shifted to the higher value of t_{Fe}^{top} while 2.5 ML Fe film is included.

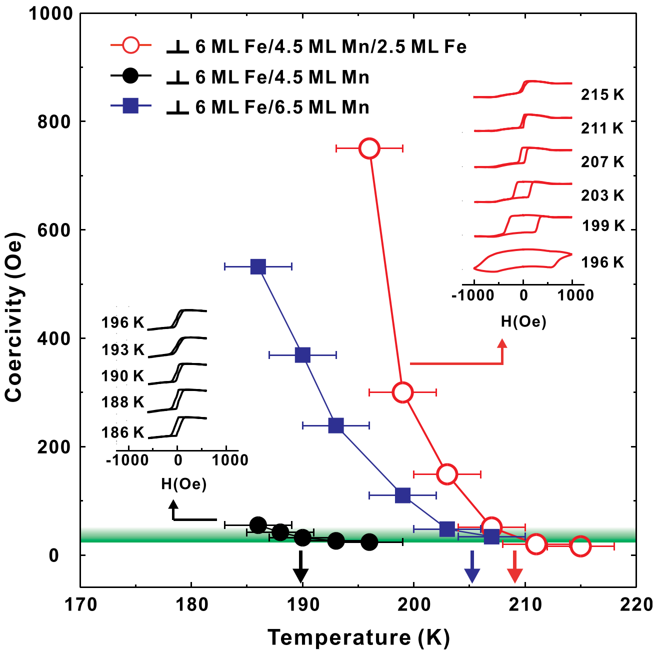

FIG. 3. Temperature-dependent perpendicular hysteresis loops and coercivity (H_c) of the perpendicularly magnetic 6 ML Fe/4.5, 6.5 ML Mn bilayers, and 6 ML Fe/4.5 ML Mn/2.5 ML Fe trilayer. The estimated $T_{Ordering}$ of Mn layers according to the threshold temperature of H_c enhancement[17,18] are indicated by the arrows at the bottom of figure. The horizontal green line (corresponding to 25–30 Oe) is defined as the reference value for the intrinsic H_c of the top 6 ML Fe layer.

work, we define 25–30 Oe as the reference value for the intrinsic H_c of the top 6 ML Fe layer. The $T_{Ordering}$ of the Mn layer can be obtained from the critical temperature that the H_c crosses over with the reference value. In the bottom of Fig. 3, the arrows display the $T_{Ordering}$ of the Mn films with different conditions. It is clear to find that the $T_{Ordering}$ of the Mn film in Fe/4.5 ML Mn bilayer is enhanced from about 190 K to 208 K while the 2.5 ML Fe underlayer was incorporated. As referring previous report,[24] the Curie temperature (T_C) of a 2.5 ML Fe ultrathin film is about 270 K. This temperature is much higher than the present $T_{Ordering}$ of the 4.5 ML Mn films in Fe/Mn bilayers ($\sim$190 K). Therefore, it is very possible that the enhanced $T_{Ordering}$ of the Mn film in Fe/Mn/2.5 ML Fe trilayer is induced by a magnetic proximity effect with the 2.5 ML Fe underlayer. Although the enhancement of $T_{Ordering}$ of Mn films and AFM-driven PMA may be limited by a use of 2.5 ML Fe film with T_C only 270 K, these characteristics are expected to be much improved if a FM layer with higher T_C is chosen.

On the other hand, for the FM/non-FM/FM trilayers, it is known that the magnetic anisotropy of the FM film could also be modulated by the long range exchange coupling across the top and bottom FM layers through the Rudermann-Kittel-Kasuya-Yosida (RKKY) interaction or the quantum well states.[26] In the case of the Fe/Mn/Fe trilayers, however, the magnetic moments of the Mn film are known to be AFM ordered and highly localized.[27,28] This could prohibit itself to be a passive medium transmitting the indirect exchange coupling.[29] Thus, the effect of interlayer coupling that helps to sustain the PMA is expected to be minor.

Finally, the present work also helps to gain more knowledge on the nature of the magnetic moments of the AFM Mn layer which are responsible for the established PMA of adjacent FM layer. Our result indicates that the PMA of Fe/Mn bilayer can be affected by the ultrathin Fe underlayer through the magnetic proximity effect. This finding confirms our previous results that the established PMA of the top Fe film is not only contributed by the AFM-FM exchange coupling at interface but is also correlated with the magnetic ordering of whole AFM Mn layer.[8]

In summary, we have reported that an AFM-induced PMA of the Fe/Mn films can be promoted by including an ultrathin Fe film as an underlayer. The enhanced PMA is attributed to an increase of magnetic ordering of the Mn film originated from a magnetic proximity effect with the Fe underlayer. The success of this approach suggests a possibility for promoting the thermal stability of a low dimensional antiferromagnet and would greatly extend our current knowledge on the control of magnetic properties of perpendicular magnetic devices composed of FM and AFM layers.

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