Antiferromagnetic coupling and perpendicular anisotropy in TbFeCo/NiO multilayers

R. Shan
Surface Physics Laboratory (State Key Laboratory) and Department of Physics, Fudan University, Shanghai 200433, China

J. Du and X. X. Zhang
Department of Physics, Hong Kong University of Science & Technology, Kowloon, Hong Kong, China

L. Sun, W. W. Lin, and H. Sang
State Key Laboratory of Solid State Microstructures, Nanjing University, Nanjing 210093, China

T. R. Gao and S. M. Zhou
Surface Physics Laboratory (State Key Laboratory) and Department of Physics, Fudan University, Shanghai 200433, China

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For Tb\(_{100-x}\)(Fe\(_{90}Co_{10}\))\(_{100-x}\) multilayers with \(x=17\) and 19, antiferromagnetic coupling is revealed by both in-plane and out-of-plane hysteresis loops at low temperatures. Magnetic perpendicular anisotropy and out-of-plane coercivity of multilayers are enhanced, in comparison to those of TbFeCo single layer films. The strength of the antiferromagnetic coupling, the perpendicular anisotropy, and out-of-plane coercivity are all reduced at high temperatures. These results can be ascribed to the weakening of antiferromagnetic ordering of NiO spins. © 2005 American Institute of Physics. [DOI: 10.1063/1.2042639]

For ferromagnet (FM)/antiferromagnet (AF) multilayers, magnetic perpendicular anisotropy (MPA), and out-of-plane coercivity, \(H_C\), can be enhanced greatly after the establishment of perpendicular exchange biasing.\(^1\)\(^2\) Although the perpendicular exchange biasing has great potential applications in ultra-high density perpendicular magnetic recording media, it is still hindered from practical applications because the out-of-plane exchange field shift, \(H_E\), usually exists. In order to avoid \(H_E\), a special field cooling procedure was used to generate a symmetrical out-of-plane hysteresis loop.\(^3\) Alternatively, symmetrical out-of-plane hysteresis loops were observed in \([\text{Co/Pt}]_N\) multilayers with thin NiO layers.\(^3\)

Studies of the interlayer coupling in FM/AF multilayers are required. First, in-plane 90° interlayer coupling between FM layers was found through AF materials such as NiO and Mn.\(^5\)\(^6\) However, for \([\text{Co/Pt}]_N/\text{NiO/}[\text{Co/Pt}]_N\) multilayers the out-of-plane interlayer coupling has been found to oscillate with a period of two-monolayer thickness as a function of AF layer thickness. More remarkably, the out-of-plane antiferromagnetic coupling (AFC) increases instead decreases as temperature is increased.\(^7\) Therefore, the mechanism of the interlayer coupling in FM/AF multilayers is unclear and needs further investigation, which can also shed light on understanding of the mechanism of the perpendicular exchange biasing. Second, since the coercivity can be tuned by the AFC, studies of the interlayer coupling are also helpful to fabrication of perpendicular magnetic recording media.

Due to strong MPA and amorphous structure, TbFeCo film is a promising candidate to be used in hybrid perpendicular magnetic recording.\(^8\) However, there is a compromise between the out-of-plane coercivity and the magnetization with respect to the composition. With the perpendicular exchange biasing, however, a large MPA might be induced in TbFeCo/NiO multilayers while the room temperature magnetization is still reasonably large. In this work, Tb\(_{100-x}\)(Fe\(_{90}Co_{10}\))\(_{100-x}\) multilayers with \(x=19\) and 17 were prepared to study the perpendicular anisotropy and interlayer coupling.

Two samples were deposited onto glass substrates in a computer-controlled multi-source sputtering system, denoted as glass\([\text{Tb}_{100-x}\text{Fe}_{90}\text{Co}_{10}\text{NiO}(3.3\text{ nm})]_N\) with \(x=19\) and 17. For comparison, 200 nm-thick single layer films were also prepared. The base pressure of the system is 8 × 10\(^{-8}\) Torr and the Ar pressure is remained at 5 mTorr during deposition. TbFeCo and NiO layers were made from Tb-FeCo composite and NiO ceramic targets by DC and RF magnetron sputtering, respectively. The TbFeCo target was formed by putting small Tb pieces on an Fe\(_{90}Co_{10}\) target. The

![FIG. 1. Typical out-of-plane hysteresis loops of \([\text{Tb}_{100-x}\text{Fe}_{90}\text{Co}_{10}\text{NiO}(3.3\text{ nm})]_N\) multilayer (right column) and \([\text{Tb}_{100-x}\text{Fe}_{90}\text{Co}_{10}\text{NiO}(200\text{ nm})\) single layer film (left column) with \(x=19\). The inset numbers refer to temperature.](image-url)
deposition rates of TbFeCo and NiO layers were 0.4 and 0.03 nm/sec, respectively. The composition of TbFeCo layers was analyzed by x-ray fluorescence. X-ray diffraction measurements showed that the TbFeCo layers are amorphous and the NiO layers have a broad diffraction peak of preferred (002) orientation. The spins of the NiO layers are located on the surface of the cone with half-apex angle $\phi$, where $\sin \phi = 1/\sqrt{3}$ and the cone axis is parallel to the film normal direction. Therefore, the projected component along the normal direction is larger than that along the film-plane. Magnetization loops at various temperatures were measured by a superconductor quantum interference device (SQUID) magnetometer. No magnetic field cooling was performed for the TbFeCo/NiO multilayers.

Figure 1 shows typical out-of-plane hysteresis loops of the TbFeCo/NiO multilayer (right column) and the single layer film (left column) with $x=19$ at temperatures from 250 to 375 K. For the TbFeCo single layer film, hysteresis loops are canted with the remanent ratio smaller than 0.5 and the saturation field larger than 1.0 T, demonstrating an in-plane anisotropy. For the TbFeCo/NiO multilayer, hysteresis loops are squared with much larger out-of-plane remanent ratio and $H_C$, as a signature of MPA. The out-of-plane $H_C$ and remanent ratio of the TbFeCo/NiO multilayer are enhanced, in comparison with those of corresponding single layer film. Similar results were also observed in [Co/Pt]/CoO and permalloy/CoO multilayers. However, for the TbFeCo/NiO multilayer near room temperature, the out-of-plane $H_C$ is equal to zero and the loop is symmetrical about the zero magnetic field. In our experiments, similar results were also found for TbFeCo/NiO multilayer and single layer film with $x=17$. At this composition, $H_C$ of the single layer film and the corresponding multilayer is about 330 and 2600 Oe at the room temperature, respectively.

Temperature dependence of coercivity for TbFeCo/NiO multilayers with $x=19$ [Fig. 2(a)] and $17$ [Fig. 2(b)] is shown in Fig. 2, which increases with decreasing temperature.

Since the magnetic properties for samples with $x=17$ and 19 are similar to each other, only the characteristic of the $x=19$ sample will be discussed. Figure 3 shows typical out-of-plane (left column) and in-plane (right column) hysteresis loops of TbFeCo/NiO multilayer with $x=19$ at low temperatures. At temperatures below 250 K, the magnetization reversal process in the out-of-plane major hysteresis loop consists of two steps and the in-plane major hysteresis loop consists of two sub-loops. The out-of-plane hysteresis loops are similar to those observed in Co–Fe/Cu multilayers with AFC and in-plane anisotropy. For TbFeCo/NiO multilayers the out-of-plane (or in-plane) hysteresis loop at low temperatures can be attributed to a combined effect of AFC between the neighboring FM layers through NiO layers and the MPA (or in-plane) anisotropy. Therefore, both the in-plane and out-of-plane AFC is observed. The occurrence of the plateau in the major hysteresis loops indicates that at low temperatures the effective MPA energy ($=\text{the difference between the MPA and the demagnetizing energy}$) or in-plane anisotropy energy $K_U$ is larger than the term $J_{\text{AFC}}/t_{\text{FM}}$, where $J_{\text{AFC}}$ and $t_{\text{FM}}$ are the AFC energy and FM layer thickness, respectively. Actually, the demagnetizing energy has great effects on the domain structure and magnetization reversal process. As revealed by the width of the plateau, the MPA energy is about two orders larger than the in-plane anisotropy energy at low temperatures, and their difference becomes smaller at high temperatures.

In order to reveal physics behind the phenomena, minor loops were measured and thus flip fields in the two configurations were identified in Fig. 3. The out-of-plane flip field is several times larger than the in-plane one at low temperatures and they approach each other as temperature increases. In the two configurations, the flip field decreases with increasing temperature. For simplicity, only the temperature dependence of the in-plane flip field is shown in Fig. 4. It is
positive at low temperatures and negative at high temperatures.

Figure 3 also shows that a net negative $H_E$ exists in the in-plane major hysteresis loop and its magnitude decreases with temperature increasing from 50 to 300 K. For example, the in-plane $H_E$ is equal to 200 Oe at 50 K and is decreased to about 100 Oe at room temperature. At low temperatures, it is unknown whether or not the out-of-plane $H_E$ exists because the major hysteresis loop cannot be saturated within the measuring magnetic field of 5 T. At least, it is equal to zero at temperatures above 250 K as shown in Figs. 1 and 3. Similar results were observed in permalloy/CoO multilayers, in which the out-of-plane $H_E$ disappears while the in-plane one exists.

For the TbFeCo/NiO multilayer, the flip field of the minor loop is related to the AFC between neighboring FM layers through NiO layers and the exchange biasing of the major hysteresis loop, that is to say, $H_{flip}=H_{AFC}+H_F$, where $H_E<0$ and the exchange field $H_{AFC}$, induced by the AFC is proportional to $J_{AFC}$. Since the magnitude of $H_{flip}$ and $H_E$ decreases as temperature is increased, as shown in Fig. 3, it can be known that $H_{AFC}$ decreases and the AFC strength becomes weak at high temperatures. Near room temperature, $H_{AFC}$ reaches zero since $H_{flip}=H_F$. This can also be seen from the phenomenon that the two-step magnetization reversal process disappears at high temperatures, as shown in Fig. 3. The weakening of the AFC strength with increasing temperature in TbFeCo/NiO multilayers is opposite to previous results in [Co/Pt]/NiO multilayers, in which the AFC becomes stronger at high temperatures.

All results in Figs. 1–4 can be explained in terms of the AF ordering of the NiO spins. First, the MPA (or in-plane anisotropy) and the out-of-plane (or in-plane) $H_E$ are strongly related to the orientation of the NiO spins. Since the normal component of NiO spins is much larger than the in-plane one, as revealed by x-ray diffraction, the MPA and out-of-plane $H_E$ are much larger than those of the in-plane one. Second, for exchange-coupled FM/AF systems, the enhanced $H_C$ is strongly related to the anisotropy of AF layers and the exchange coupling energy. These two physical quantities decrease with increasing temperature since the AF ordering of the NiO spins becomes weak due to thermal fluctuations.

The reduction of $H_C$ with increasing temperature is therefore easily understood. Third, although it is unknown whether or not the AFC strength in the out-of-plane is equal to that of the in-plane, it is the first time that the AFC is observed in both the out-of-plane and in-plane hysteresis loops. The AFC strength decreases with increasing temperature and is suggested to be induced by the AF ordering of spins in NiO layers. Finally, the variation of the flip field with temperature in Fig. 4 can be understood because $H_{flip}=H_{AFC}+H_E$ and $H_{AFC}$ and $H_E$ decrease with increasing temperature.

For Tb$_x$(Fe$_{90}$Co$_{10}$)$_{100-x}$(40 nm)/NiO(3.3 nm) multilayers with $x=19$, at room temperature, the out-of-plane coercivity is 4200 Oe, the remanent ratio 0.7, and the magnetization about 330 emu/cm$^3$. The out-of-plane hysteresis loop is symmetrical about the zero magnetic field. More importantly, the variation of coercivity with temperature matches the heat-assisted perpendicular magnetic recording. Therefore, TbFeCo/NiO multilayers might become potential candidate media for hybrid perpendicular magnetic recording.

In summary, for Tb$_x$(Fe$_{90}$Co$_{10}$)$_{100-x}$(40 nm)/NiO(3.3 nm) multilayers with $x=17$ and 19, the enhanced out-of-plane $H_E$ and formation of MPA have been observed, in comparison with those of corresponding single layer films. For TbFeCo/NiO multilayers, the AFC has been observed in both the out-of-plane and in-plane hysteresis loops. The AFC strength, MPA, and out-of-plane coercivity become weaker with increasing temperature, which can be understood in terms of thermal fluctuations of the NiO spins.

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