CIP spin torque effect in the spin valve pinned with an oxide antiferromagnetic layer

Nguyen Chi Thuan1, Nguyen Van Dai1, Dao Nguyen Hoai Nam1,2, Nguyen Xuan Phuc1 and Le Van Hong1
1 Institute of Materials Science, Vietnam Academy of Science and Technology, 18 Hoang Quoc Viet Road, Cau Giay Distr., Hanoi, Vietnam
2 Department of Materials Science and Engineering, University of Virginia, Virginia 22903, USA
E-mail: thuannc@ims.vast.ac.vn

Abstract. Spin valve Ni0.85Co0.15O/Co85Fe15/Cu/Co85Fe15 was manufactured by a RF magnetron sputtering system. M(H) and R(H) characteristics of the spin valve were measured in CIP configuration at room temperature has a magnetoresistance ratio of about 8% and a high exchange bias at room temperature. The current density and angle between the applied magnetic field and injection current were changed in an aim to observe their effects on MR and exchange bias of the spin valve. The current density and angle strongly affect MR and exchange bias. Both MR and exchange bias clearly decrease in dependence of the current density and direction of the magnetic field. It is supposed to be related with a current-induced spin torque in device.

Keywords: GMR, exchange bias, spin torque, effect.

1. Introduction
The NiFe and CoFe based spin-valves pinned with an antiferromagnetic layer are of interest in the development of the high density magnetoresistance (MR) heads and sensors. Various antiferromagnetic film layers such as FeMn, NiMn, and oxidic layers such as NiO have been used as a biasing layer, which is exchange coupled with the NiFe and CoFe sensing films [1, 2]. The spin valve effect is associated with relative orientation of magnetization vectors in adjacent magnetic layers, which are very sensitive to crystallographic orientations and interface roughness of layers [3]. A theoretical calculation by Inoue et al. [4] supposed that the spin-dependent scattering factor of CoFe is larger than that of NiFe. Therefore, it is expected that the MR ratio could be improved in the spin valve Ni1-xCo,O/FeCo/Cu/FeCo. Shirotta et al. [5] obtained MR ratio of 7.9% for NiO/2F/2.6Cu/1.6F/5Si-N spin-valve device, where F is Co90Fe10. Egelhoff et al. [6] has improved the MR ratio up to over 20% at room temperature for this kind of spin-valve device with two pinning layers in the symmetrical configuration. Using a ferromagnetic Fe15Co85 buffer layer with an appropriated thickness we improved the MR ratio [7], which was explained as a result of improving the plane magnetic anisotropy of the antiferromagnetic Ni1-xCo,O layer.

Generally, the ferromagnetic (FM) material exhibits symmetric hysteresis loop centered at zero magnetic field (H = 0). As the first, Meiklejohn and Bean observed a displacement of the hysteresis loop of slightly oxidized Co particles from H = 0. It was explained as a result of the exchange
coupling between the surface antiferromagnetic (AFM) Co oxides and the FM Co core [8, 9]. This exchange coupling can be better revealed in the FM/AFM bilayers such as NiFe/FeMn, NiFe/NiO [10], or Ni$_{1-x}$Co$_x$/FeCo bilayer presented in this paper. When the FM/AFM bilayer was cooled in a magnetic field from temperatures above Neél temperature $T_N$ of the AFM to lower temperatures, exchange coupling has been locked in. Effectively the hysteresis loop is shifted from $H = 0$ by an amount called the exchanged field $H_{EX}$, which can reach as high as of 1 KOe. The shift of hysteresis loop is substantially accompanied by coercivity $H_C$ which is much larger than the intrinsic value of the FM layer. Besides, it depends on anisotropy axis, in which the exchange coupling in FM/AFM layer was locked. According to theoretical calculations the exchange coupling at the FM/AFM interface depends on anisotropic axis of the constituent magnetic layers, consequently the exchange coupling reveals the angular dependence.

In this work we present the angular dependence of the exchange coupling of the spin valve Fe$_{15}$Co$_{85}$(1.6 nm)/Ni$_{0.85}$Co$_{0.15}$O(40 nm)/Fe$_{15}$Co$_{85}$(3 nm)/Cu(3.8 nm)/Fe$_{15}$Co$_{85}$(4.5 nm). In general, the spin transfer or spin torque in a spin-valve (or MTJ) structure is expected to be strong when spin valve works in the CPP (current perpendicular to plane) configuration [11]. Some recent results on spin torque in spin valve pinned by a metal antiferromagnetic layer, working in CPP configuration were reported by [12, 13]. Recently, Tang et al. [14] reported a new result for the case of spin valve working in CIP configuration. It showed that the spin torque effect occurs only when the sweeping magnetic field induced by the injection current is antiparallel to the exchange-bias field. Exchange bias of spin valve systematically decreases when increasing the flowing current. Their observation confirmed that the critical spin torque induced current in an antiferromagnet is smaller than the typical value for switching in a ferromagnet.

In this report, we present an observation of the current induced spin torque of Fe$_{15}$Co$_{85}$(1.6 nm)/Ni$_{0.85}$Co$_{0.15}$O(40 nm)/Fe$_{15}$Co$_{85}$(3 nm)/Cu(3.8 nm)/Fe$_{15}$Co$_{85}$(4.5 nm) valve spin working in CIP configuration. We also present a new result of study on the dependence of exchange bias upon the angle between the external applied field and the exchange field.

2. Experimental

Fe$_{15}$Co$_{85}$(1.6 nm)/Ni$_{0.85}$Co$_{0.15}$O(40 nm)/Fe$_{15}$Co$_{85}$(3 nm)/Cu(3.8 nm)/Fe$_{15}$Co$_{85}$(4.5 nm) samples were fabricated by the successive deposition of layers in a magnetron sputtering system (EDWARDS AUTO 306) equipped with 3 targets, a DC and RF source in a chamber with the base vacuum of $8 \times 10^{-6}$ mBar. The metallic alloy layer Fe$_{15}$Co$_{85}$ and non-magnetic Cu have been deposited in Ar gas of pressure about $5 \times 10^{-3}$ mBar and $3 \times 10^{-3}$ mBar, respectively. Ni$_{0.85}$Co$_{0.15}$O was deposited in Ar gas of pressure of $3 \times 10^{-3}$ mBar, containing 20% of oxygen. A quartz vibrating thickness-meter has controlled thickness of all layers during the deposition processing. An external magnetic field of 500 Oe was applied in-plane during the deposition processing to create unidirectional magnetic exchange field. We found that inserting a CoFe seed layer with a pertinent thickness would help stabilize the antiferromagnetic layer and considerably improve the magnetoresistance signal, probably due to an improvement of the in-plane anisotropy of the magnetic layers deposited afterward. Quality of the films was examined by X-ray diffraction, energy-dispersive X-ray spectroscopy, magnetization, and conductance techniques. Resistance (R) and magnetoresistance $\{MR_{tot}=(R_{\uparrow\downarrow}-R_{\downarrow\uparrow})\times 100%/R_{\downarrow\uparrow}\}$ of the spin valves were measured by the standard four-probe techniques in an external magnetic field aligned both in-plane and out-of-plane under various angles at room temperature by a Quantum Design PPMS.

3. Result and discussion

In this investigation two experiments were done, the first observed the angular dependence of exchange coupling in FM/AFM layer by measuring MR and exchange field $H_{EX}$ of the spin valve in dependence on angle between the magnetic measuring field and the magnetic field that is applied in aim of creating an initial exchange anisotropy in the spin valves, the second observed the spin torque induced by sweeping current in CIP configuration. According to the aims we performed two measurement configurations as presented in figure 1, the in-plane measurement configuration (figure
1b) and the out-of-plane measurement configuration (figure 1c).

![Spin valve structure](image)

**Figure 1.** Spin valve structure (a), in-plane measurement configuration (b) and out-of-plane measurement configuration (c).

As seen at this figure, in the case of the in-plane configuration the injection current is aligned along y-axis, perpendicular to the pinning magnetic field \(H_P\). Conversely, the measuring magnetic field \(H_M\) is applied in-plane, respecting the pinning magnetic field under an angle \(\theta_F\), which changed in values of 0, 15, 30, 45, 60, 75, and 90 degrees. The measured results are presented in figure 2. It shows that MR and \(H_{EX}\) of the spin valve significantly decreases when angle \(\theta_F\) was increased. According to the two models proposed by Mauri [15] and Malozemoff [16] the exchange field is proportional to \((A_{AFM}K_{AFM})^{0.5}\), where \(A_{AFM}\) and \(K_{AFM}\) are the exchange constant and the anisotropy of the AFM layer, respectively. The exchange field conclusively demonstrates an unidirectional behavior and then depends on angles between the measuring magnetic field and the anisotropy axis. The most general angular dependence of the exchange field is presented as follows [17]

\[
H_{ex} = \sum_n b_n \cos n\theta ,
\]

where \(b_n\) is a constant and \(n\) is a positive integer. According to equation (1) the exchange field decreases when \(\theta\) is increased. It well agrees with the obtained experimental results \(H_{EX}\), which has been evaluated as \(H_{EX}=(H_↑ + H_↓)/2\), where arrows \(\uparrow\) and \(\downarrow\) mark the direction of the measurement magnetic field, \(H_↑\) and \(H_↓\) the fields at which the MR of spin valve reduces to value of MR\(_{max}/2\) in branch \(H<0\) and conversely the MR of spin valve rises up to value of MR\(_{max}/2\) in branch \(H>0\), respectively.

![MR ratio versus angle](image)

**Figure 2.** The MR ratio versus angle \(\theta_F\) measured in the in-plane configuration.

![MR ratio versus angle](image)

**Figure 3.** The MR ratio versus angle \(\theta_F\) measured in the out-of-plane configuration.
Figure 4. The dependence of MR and $H_{EX}$ on angle $\theta_F$ in two configuration measurements.

Table 1. MR ratio and $H_{EX}$ in two configuration measurements with varying angle $\theta_F$.

| $\theta_F$ (degree) | 0  | 15 | 30 | 45 | 60 | 75 | 80 | 85 | 88 | 89 | 90 |
|---------------------|----|----|----|----|----|----|----|----|----|----|----|
| MR in-plane (%)     | 8.2| 7.83| 7.10| 6.10| 5.10| 4.33|     | 4.00|    |    |    |
| $H_{EX}$ in-plane (Oe) | 244| 171| 155| 143| 131| 122|     | 115|    |    |    |
| MR out-of-plane (%) | 8.2| 8.13| 8.11| 8.09| 8.06| 8.04| 8.00| 7.92| 7.57| 6.89| 4.82|
| $H_{EX}$ out-of-plane (Oe) | 244| 252| 285| 350| 504| 995| 1536| 2253| 3705| 4504| 5036|

By this way $H_{EX}$ of the spin valve was evaluated and presented in table 1 as well as in figure 4. As shown in table 1 the obtained exchange field decreases from 170 to 115 Oe when $\theta_F$ was increased from 0 to 90 degree. According to Tang [14] at the FM/AFM interface the moments of electrons flowing from the FM into the AFM are not parallel to the AFM. Consequently they induce torques on moments in the antiferromagnetic layer. In addition we also observe a decrease of MR of spin valve when the angle $\theta_F$ increases. It may be related with a canting of magnetization moment in the FM layer due to the measuring field. In the case of the out-of-plane measurement configuration, the magnetic field measurement was applied in the $z$-$x$ plane, perpendicular to the spin valve plane, respecting the anisotropy axis under angles from 0 to 90 degrees. It means that by this configuration we can observe the perpendicular exchange coupling in the spin valve. The obtained results are presented in figure 3. We receive absolutely different dependence of MR and $H_{EX}$ on the applied magnetic field. In contrary to the case of in-plane configuration the $H_{EX}$ in this case much increases in dependence of the angle $\theta_F$ beside a quite unchanged in MR. $H_{EX}$ raises up to higher than 1 kOe at the $\theta_F$ equal to 75 degree. This very large value of the recorded perpendicular $H_{EX}$ is probably due to the domination of the in-plane anisotropy of the FM/AFM bilayer.

Our second study is observing spin torque effect in CIP induced by pumping different currents through the spin valve. The obtained $R(H)$ and MR($H$) curves are presented in figure 5a and figure 5b, respectively. Since the current is flowing in the layer planes, it produces a magnetic field which is perpendicular to the sweeping field, and then the real magnetic field acting on the pinned layer, which is shown in figure 1b, rotates by an angle $\theta_F$. The angle $\theta_F$ increases with increasing current. Hence we receive the same situation as in the case of angular dependence of the exchange bias, presented previously.
As seen in figure 5, with increasing current the reversal field of the free layer seems to be unaffected, while that of the pinned layer (in both field sweeping directions $H>0$ and $H<0$) is substantially suppressed. It is remarkabe that the results in figure 5 just resemble those previously observed in spin valves with a metallic antiferromagnetic layer, where electron flow induces a torque of its magnetic moment, therefore leading to a change in the exchange bias [12, 14]. In our case, since the in-plane current is confined to flow only in the CoFe(3.0 nm)/Cu(3.8 nm)/CoFe(4.5 nm) top layers, there would be no such current-induced spin torques in the antiferromagnetic layer. Our results in figure 5 show quite the same results obtained in our first experiment. In the same way as presented previously we evaluated $H_{\text{EX}}$ values for all the measurement lines. It clearly shows a reduction of $H_{\text{EX}}$ from 240 to about 85 Oe, induced by the injection current. The critical current density which noticeably reduced $H_{\text{EX}}$ has been estimated at about $10^9$ A/m$^2$. Note that this current density is more than about 3 orders higher than the switching current reported in Ref. 14 for an antiferromagnet ($10^6$ A/m$^2$) and still below the typical level for switching a ferromagnet ($10^9$÷$10^{11}$ A/m$^2$). Probably, the current flowing in the CoFe(3.0 nm)/Cu(3.8 nm)/CoFe(4.5 nm) top layers induces a magnetic field which rotates electrons with a force acting on the antiferromagnetic layer under angles in range from 0 to 90 degree. Consequently a torque of moments in the AFM was induced and exchange bias decreases with increasing of the injection current. As seen in figure 5a resistance of spin valve rises up a little when applying the current higher 50 mA. It is related to the Joule heating which was confirmed in Ref. [18] that the Joule heating by flowing current plays a lesser role in the depression of $H_{\text{EX}}$ compared to the current induced effect.

4. Conclusions
Spin valve $\text{Ni}_{0.85}\text{Co}_{0.15}\text{O/Co}_{85}\text{Fe}_{15}/\text{Cu/Co}_{85}\text{Fe}_{15}$ was successfully manufactured by a RF magnetron sputtering. A depression of $H_{\text{EX}}$ in dependence of the angle between applied magnetic field and injection current were observed. $H_{\text{EX}}$ decreases with increasing the angle in the case of the in-plane configuration of CIP measurement. Conversely $H_{\text{EX}}$ significantly increases with increasing the angle in case of the out-of-plane configuration. It is supposed to be related with the anisotropy of the antiferromagnetic layer. A depression of $H_{\text{EX}}$ due to the spin torque effect induced by the injection current in CIP measurement configuration was also observed. It is supposed that the torque of moments in AFM is an effect induced by the flow of electrons which is not parallel to AFM layer.

References
[1] Tsang C, Fontana R E, Lin T, Heim D E, Speriosu V S, Gurney B A and Williams M L 1994 IEEE Trans. Magn. 30 3801
[2] Lin T, Tsang C, Fontana R E and Howard J K 1995 IEEE Trans. Magn. 31 2585
[3] Han D-H, Zhu J-G and Judy J H 1997 J. Appl. Phys. 81 4996
Acknowledgments

This work was done with the support of Grant 4.076.06 in the Fundamental Research Program of Vietnam (2006-2008) and the Basic Research Project of IMS under grant number CS06.08. The technique support in part by the National Key Laboratory for Electronic Materials and Devices is acknowledged.