Influence of CoFe and NiFe pinned layers on sensitivity of planar Hall biosensors based on spin-valve structures

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Abstract
This paper deals with the magnetization, magnetoresistance and planar Hall effect (PHE) of NiFe(10)/Cu(1.2)/NiFe(tₚ)/IrMn(15) (nm) and NiFe(10)/Cu(1.2)/CoFe(tₚ)/IrMn(15) (nm) spin-valve structures with various thicknesses of pinned layer tₚ = 2, 6, 9, 12 nm and a fixed free layer NiFe of t_f = 10 nm. Experimental investigations are performed for 50 × 50 μm junctions fabricated using lithography technique. The results show that the thinner the pinned layers, the higher is the PHE sensitivity obtained in both systems. In addition, in the spin-valve structures with the same pinned layer thickness, the CoFe-based system exhibits higher magnetoresistive ratio, but lower PHE sensitivity with respect to those of the FeNi-based system. The results are discussed in terms of the spin twist as well as the coherent rotation of the magnetization in the individual ferromagnetic layers. The highest PHE sensitivity S of 110 μV (kA m⁻¹)⁻¹ has been obtained in the FeNi-based spin-valve structure with t_p = 2 nm. This result is rather promising for the spintronic biochip developments.

Keywords: planar Hall effect, Hall sensor, magnetic sensor, biochip, bead array counter microchip

Classification numbers: 2.00, 4.00, 4.10, 5.00, 5.02, 6.09, 6.10

1. Introduction

The spin valve, which was known as a simple embodiment of the giant magnetoresistance (GMR) effect, was first termed by Dieny et al [1] and has recently played a key role in high-density magnetic recording heads and magnetic biosensor due to their high magnetoresistance (MR) ratio in low field and linear MR response [2-4]. Its structure typically consists of two ferromagnetic (FM) layers separated by a nonmagnetic conductor whose thickness is smaller than the mean-free path of electrons. The magnetic layers are uncoupled or weakly coupled in contrast to the generally strong antiferromagnetic (AFM) state interaction in Fe–Cr-like multilayer; thus the magnetization of an FM layer with uniaxial anisotropy can be rotated freely by a small applied magnetic field in the film plane, while the magnetization of the other magnetic layer has unidirectional anisotropy pinned by exchange bias coupling from the AFM layer. Recently, this effect has been well developed for biochip applications due to its large resistance change in small magnetic field range [5-11]. The GMR effect is related to the switching of magnetic domain. It has low signal-to-noise ratio (SNR), leading to a high error in detections of the small stray field. The planar Hall effect (PHE), however, is related to the rotation process of magnetic domain and originates as the anisotropic magnetoresistance. This effect exhibits a nano-tesla sensitivity and rather high SNR, so
it has received great attention for magnetic bead detections and biosensor designs [5–8, 12, 13]. The transverse voltage on a planar Hall cross depends on the orientation of the magnetization in the ferromagnetic layer with respect to the longitudinal sensing current. Thus, a large PHE is expected to be observed in the exchange coupling based structures because they can ensure a sufficient uniaxial anisotropy with well-defined single domain state to introduce a unidirectional anisotropy. Recently, Nguyen et al [10] have found that the sensor signal can be further improved by using spin-valve structure of NiFe(6)/Cu(3.5)/NiFe(3)/IrMn(10) (nm) in the dimension of 3 × 3 μm when detecting the 2.8 μm magnetic beads. Through our recent research, we see that spin-valve structure with thickness of the Cu layer being 1.2 nm is better [14]. The present paper deals with the influence of pinned ferromagnetic layers on magnetic field sensitivity of PHE sensors based on spin-valve structures. This has been realized in NiFe(10)/Cu(1.2)/NiFe(tp)/IrMn(15) (nm) and NiFe(10)/Cu(1.2)/CoFe(tp)/IrMn(15) (nm) structures with various thicknesses of pinned layer tp = 2, 6, 9, 12 nm and a fixed free layer NiFe of tf = 10 nm. The objective of this study is to optimize the spin-valve structure for magnetic bead detections.

2. Experimental procedures

The thin films with typical spin-valve structure of Ta(5)/NiFe(10)/Cu(1.2)/NiFe(tp)/IrMn(15)/Ta(5) (nm) and NiFe(10)/Cu(1.2)/CoFe(tp)/IrMn(15) (nm) with free ferromagnetic (FFM) layer thicknesses tf = 2, 6, 9, 12 nm and pinned ferromagnetic (PFM) layer thickness NiFe of tf = 10 nm are fabricated by using magnetron sputtering system with the base pressure less than 3 × 10−7 mTorr. The spin-valve structures were sputtered on SiO2 wafer at room temperature with Ar working pressure of 3 × 10−3 mTorr. During the sputtering process, a uniform magnetic field of Hf = 32000 A m−1 was applied in the plane parallel to the Ox-direction of the films. This magnetic field induces a magnetic anisotropy in the FFM and PFM layers and then aligns the pinning direction of the AFM IrMn layer. The PHE sensors were fabricated by using photolithography technique into four-electrode bars with the patterned size of 50 × 50 μm (figure 1(a)). The sensors were passivated by sputtering a 150 nm thick Si3N4 layer to protect against the fluid used during the experimentation. The bead array counter (BARC) microchip was fabricated by integrating ten single sensor patterns as shown in figure 1(b).

The PHE characteristics of sensors were measured at room temperature by using a nanovoltmeter in the external magnetic fields Hf up to 4 kA m−1 applied along Oy direction and sensing currents Is of 1 mA. Longitudinal magneto-resistance was measured by means of a collinear four-point probe method for samples with the size of 2 × 10 mm in magnetic field and sensing current applied along Ox-direction. Magnetization was measured by using a Lakeshore 7400 vibrating sample magnetometer.

3. Results and discussion

Figure 2 presents the magnetization data of spin-valve structures Ta(5)/NiFe(10)/Cu(1.2)/CoFe(2)/IrMn(15)/Ta(5) (nm) called sample 1 and Ta(5)/NiFe(10)/Cu(1.2)/NiFe(2)/IrMn(15)/Ta(5) (nm) called sample 2. It is clearly seen that all samples exhibit two hysteresis loops corresponding to the magnetization processes of the FFM and PFM layers. Magnetic reversed process of the sample 2 starts and finishes sooner than that of sample 1. For sample 2, it starts from magnetic field value of 700 A m−1 and final parallel configuration of individual layer magnetization seems to be completed at the magnetic field of Hf = 540 A m−1. Whereas, for sample 1, these parameters are 210 and 610 A m−1, respectively. The PFM layer is expected to dominate the sensor response at low magnetic fields. The values of the coercivity (Hc) and exchange coupling (Hex) [14] fields determined from the first hysteresis loop are listed in table 1. There is a clear difference in values of Hc and Hex between structures having the pinned layers CoFe and NiFe. The difference is explained by exchange coupled field between the pinned layer and the free layer via the Cu non-magnetic layer. This field between the CoFe and NiFe layers is larger than that between the NiFe and Cu layers.

Shown in figure 3 are the PHE voltage profiles of both of samples, VpHE, as a function of the applied field. Firstly, the PHE voltage initially develops rather fast at low fields reaching a maximal value at H < 1100 A m−1 for the sample 1 and H < 3000 A m−1 for the sample 2 and finally decreases with further increasing of the magnetic fields. It is interesting to note that the sensor sensitivity S(= dV/dH, see below) of

![Figure 1](image_url) (a) Top view micrograph of the single 50 μm ×50 μm planar Hall resistance (PHR) cross. The pinning direction Hf, as well as the direction of the bias field Hy and sensing current Is are indicated. (b) The BARC including ten of single PHE sensors (with eight single sensors in the two middle lines and one single sensor in each edge line).
Table 1. Values of sensor sensitivity ($S$), coercive ($H_c$), anisotropy ($H_k$), exchange coupling ($H_{ex}$) fields for spin-valve system with different pinned layer.

| Pinned layer | $T_P$ (nm) | $S$ (µV kA$^{-1}$ m) | $H_c$ (A m$^{-1}$) | $H_k$ (A m$^{-1}$) | $H_{ex}$ (A m$^{-1}$) |
|--------------|------------|----------------------|-------------------|-------------------|----------------------|
| CoFe         | 2          | 27                   | 140               | 1000              | 3000                 |
| NiFe         | 2          | 68.0                 | 70                | 230               | 1140                 |

Figure 2. Magnetic hysteresis loops data of spin-valve structures of samples 1 and 2.

Figure 3. Low field PHE profiles measured in Ta(5)/NiFe(10)/Cu(1.2)/NiFe(2)/IrMn(15)/Ta(5) (nm) and Ta(5)/NiFe(10)/Cu(1.2)/CoFe(2)/IrMn(15)/Ta(5) (nm) spin-valve structure.

Figure 4. Effect of thickness of the CoFe and NiFe pinned layer on PHE sensor sensitivity $S$.

The magnetization is pinned in different directions from the easy axis (i.e. $\theta_p \neq 0$) [16]. In this context, the twisted part can be assumed to be eliminated in the structure with thin pinned layer $T_P \leq 2$ nm [14]. Practically, the maximal PHE voltage and the highest sensitivity of sensor were observed in this configuration. For the thinner and softer (NiFe) PFM layers, the magnetic influence and then the twist part can be established near NM/FFM interface only. Thus it enhances the PHE voltage.

Inversely, with the PFM layer having thicker and harder (CoFe) layers, the twist part will be developed so the rotation of the magnetization in the FFM is more difficult. Therefore, PHE voltage is smaller. This is shown in figure 4.

Here, the most interesting result is that while the maximum PHE voltage of sample 1 is 50 µV at $H \sim$ 3000 A m$^{-1}$ with sensitivity 27 µV (kA m$^{-1}$), then sample 2 reaches the maximum PHE voltage value about 62 µV at $H \sim$ 1100 A m$^{-1}$ and this spin-valve configuration shows a sensor sensitivity as large as 68 µV (kA m$^{-1}$)$^{-1}$.

4. Conclusion

The influence of the different pinned layer softness and thickness on the sensitivity of PHE sensor based on the spin-valve structure of NiFe(10)/Cu(1.2)/NiFe or CoFe($T_P$)/IrMn(15) (nm) with size of 50 µm $\times$ 50 µm has been studied. The results show that the thinner and softer pinned FM layers enhance the PHE signal, whereas the thicker pinned and harder FM layers lower the PHE signal. The results are discussed in terms of the spin twist as well as to the coherent rotation of the magnetization in the individual FM layers. This optimization is rather promising for spintronic biochip developments.
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References

[1] Dieny B, Speriosu V S, Metin S, Parkin S S P, Gurney B A, Baumgart P and Wilhoit D R 1991 J. Appl. Phys. 69 4774
[2] Lacheisserie E T, Gignoux D and Schlenker M 2002 Magnetism-II Fundamentals (New York: Springer)
[3] Leal J L and Kryder M H 1996 J. Appl. Phys. 79 2801
[4] Monsma D J 1998 The Spin Valve Transistor (Einschede, The Netherlands: University of Twente)
[5] Schuhl A, Nguyen F V D and Childress J R 1995 Appl. Phys. Lett. 66 2751
[6] Nguyen F V D, Schuhl A, Childress J R and Sussiau M 1996 Sensors Actuators A 53 256
[7] Ejsing L, Hansen M F, Menon A K, Ferreira H A, Graham D L and Freitas P P 2004 Appl. Phys. Lett. 84 4729
[8] Ejsing L, Hansen M F, Menon A K, Ferreira H A, Graham D L and Freitas P P 2005 J. Magn. Magn. Mater. 293 677
[9] Bui D T, Tran Q H, Nguyen T T, Tran M D, Nguyen H D and Kim C G 2008 J. Appl. Phys. 104 074701
[10] Nguyen T T, Rao B P, Nguyen H D and Kim C G 2007 Phys. Status Solidi a 204 4053
[11] Tran Q H, Pham H Q, Nguyen T T, Oh S J, Bharat B and Kim C G 2007 Phys. Status Solidi b 244 4431
[12] Maekawa S 2006 Concepts in Spin Electronics (Oxford: Oxford University Press)
[13] Chappert C, Fert A and Nguyen F V D 2007 Nature Mater. 6 813
[14] Bui D T, Le V C, Tran Q H, Do T H G, Tran M D, Nguyen H D and Kim C G 2009 IEEE Trans. Magn. 45 2378
[15] Nguyen T T, Rao B P, Nguyen H D and Kim C G 2007 Phys. Status Solidi a 204 4053
[16] Wang S, Xu Y and Xia K 2008 Phys. Rev. B 77 184430