Optimization of planar Hall effect sensor for magnetic bead detection using spin-valve NiFe/Cu/NiFe/IrMn structures

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Abstract. Present paper deals with the planar Hall effect (PHE) of Ta(5 nm)/NiFe(tf)/Cu(1.2 nm)/NiFe(tp)/IrMn(15 nm)/Ta(5 nm) spin-valve structures. Experimental investigations are performed for 50 × 50 μm² junctions with various thicknesses of free and pinned layer tf = 4, 8, 10, 15, 20 nm and tp = 2, 3, 6, 8, 9, 12 nm. The results show that the thicker free layers, the higher PHE signal is obtained. In addition, the thicker pinned layers, the lower PHE signal. The highest PHE sensitivity S of 15.6 mΩ/Oe is obtained in the spin-valve configuration with tf = 20 nm and tp = 2 nm. This optimum structure is rather promising for micro magnetic bead detections.

Keywords: Biosensors, Hall effect, magnetization reversal, magnetoresistance.

1. Introduction

Magnetic label detection is usually accompanied by using giant magnetoresistance effect, PHE, as well as magnetic tunneling junctions. Among them, PHE has recently been receiving great attention for spintronic biosensor design thanks to its nano-Tesla sensitivity and high signal-to-noise ratio [1-6]. PHE is based on the anisotropic magnetoresistance (AMR) of ferromagnetic (FM) materials. The transverse voltage on a planar Hall cross depends on the orientation of the magnetization of the free ferromagnetic (FFM) layer with respect to the longitudinal current running through the material. Thus, the large PHE is expected to be observed in exchange coupling based structures because they can ensure a sufficient uniaxial anisotropy with well defined single domain state to introduce an unidirectional anisotropy. For this purpose, Ejisng et al. [3, 4] have reported a single PHE sensor of NiFe/IrMn/NiFe. Furthermore, a PHE magnetic bead array counter microchip integrating 24 single sensors based on a simple NiFe/IrMn bilayer structure was successfully prepared [5]. Recently, Thanh et al. [6] have found that the sensor signal can be further improved by using spin-valve structure of Ta(5 nm)/NiFe (6 nm)/Cu (3.5 nm)/NiFe (3 nm)/IrMn (10 nm)/Ta (5 nm) with the size of 3×3 μm² when detecting the 2.8 μm magnetic beads.

The present paper deals with studies of the sensitivity dependence on the thickness of the individual ferromagnetic layers in patterned 50×50 μm² PHE sensor based on Ta/NiFe/Cu/NiFe/IrMn/Ta spin-valve structure. This PHE sensor has been proposed to apply to magnetic bead detection.
2. Experimental
Spin-valve Ta(5 nm)/NiFe(1.2 nm)/NiFe(15 nm)/Ta(5 nm) structures (with \( t_f = 4, 8, 10, 15, 20 \) nm and \( t_p = 2, 3, 6, 8, 9, 12 \) nm) are fabricated by DC magnetron sputtering system with the base pressure less than \( 7 \times 10^{-7} \) mTorr. The spin-valve structures are sputtered on SiO\(_2\) wafer at room temperature with Argon working pressure of \( 3 \times 10^{-3} \) mTorr. During the sputtering process, a uniform magnetic field of \( H_x = 400 \) Oe is applied in plane of the films, parallel to the \( Ox \) direction. This magnetic field induces a magnetic anisotropy in the free and pinned ferromagnetic (PFM) layers and then aligns the pinning direction of the antiferromagnetic (AFM) IrMn layer. The PHE sensors are structured by using lithography techniques into four-electrode bars with the patterned size of \( 50 \times 50 \) \( \mu \)m\(^2\) (figure 1a) The sensors were passivated by a sputtered 150 nm thick Si\(_3\)N\(_4\) layer to protect against the fluid used during experimentation. The bead array counter (BARC) microchip was fabricated by integrating 10 sensor patterns as shown in figure 1b.

The PHE characteristics of sensors was measured by using a nanovoltmeter in external magnetic fields \( H_y \) up to 30 Oe applied along \( Oy \) direction and sensing currents \( I_x \) of 1 mA. Magnetization is measured by means of a Lakeshore 7400 vibrating sample magnetometer (VSM) on defined 12\( \times \)12 mm\(^2\) films.

![Figure 1](image)

Figure 1. (a) - Top view micrograph of the single 50\( \times \)50 \( \mu \)m\(^2\) PHR cross. The pinning direction \( H_x \) as well as the direction of the bias field \( H_y \) and sensing current \( I_x \) are indicated. (b) – the bead array counter microchip including 10 of single PHE sensors (with 8 single sensors in the two middle lines and 1 single sensor in each edge line).

3. Results and discussion

3.1. Fixed pinned layer thickness system
Figure 2a presents magnetization data of spin-valve Ta(5 nm)/NiFe(1.2 nm)/NiFe(3 nm)/IrMn(15 nm)/Ta(5 nm) structures with different thickness \( (t_f) \) from 4 to 20 nm. It is clearly seen that all samples exhibit two hysteresis loops. The magnetization accounting from the first loop increases with increasing \( x \) while that from the second loops is almost constant. These two hysteresis loops are attributed to the free and pinned layers, respectively. The free layer is expected to dominate the sensor response at low magnetic fields. The values of the anisotropy \( (H_K) \) and exchange coupling \( (H_{ex}) \) fields determined from these magnetization data are collected and listed in table 1. Note that \( H_K \) and \( H_{ex} \) are almost constant for \( t_f > 10 \) nm.

Shown in figure 2b is the sensor voltage as a function of the applied fields. It can be seen from this figure that the PHE voltage initially develops rather fast at low fields, reaching a maximal value at \( H \approx 10 \) Oe and finally decreases with further increase of the magnetic fields. For this fixed pinned layer spin-valve system, however, the maximal value of the PHE voltage increases with increasing free layer thickness. It increases from the value of 15 \( \mu \)V for sample with \( t_f = 4 \) nm to the value of 48 \( \mu \)V for \( t_f = 20 \) nm. Consequently, the sensor sensitivity \( S (=dV/dH, \text{see below}) \) is enhanced from the value of 1.7 m\( \Omega \)/Oe to 7.6 m\( \Omega \)/Oe, respectively.
It is well known that when the magnetization vector $M$ makes an angle $\theta$ with easy axis along the Ox direction (and/or with $I_x$), the transverse induced PHE voltage $V_{\text{PHE}}$ (or $V_y$) parallel to Oy direction is given as follows:

$$V_y = I_x \Delta R \sin \theta \cos \theta,$$  

(1)

where $\Delta R = (\rho_\parallel - \rho_\perp)/t$ with $\rho_\parallel$ and $\rho_\perp$ are the resistivity measured with the current parallel and perpendicular to the magnetization, respectively; $t_f$ is the free ferromagnetic layer thickness.

Typically, these $V_{\text{PHE}}(H)$ curves are fitted well by using the single domain model [7] with the magnetic energy per unit of the magnetic layer. In this case, the Stoner-Wohlfarth energy can be expressed as:

$$E_{\text{FM}} = K_u t \sin^2 \theta_f - M_s t H \cos(\alpha - \theta_f) - J \cos(\theta_f - \theta_p).$$  

(2)

Here, the $\theta_f$ and $\theta_p$ are the angles between magnetization of the free and pinned layers and easy axis direction, respectively; $K_u (= H_K/2M_s)$ is the effective anisotropy constant, $M_s$ is the saturation magnetization of the free layer and $J$ is the interlayer coupling constant that can be extracted from the relationship with the exchange coupling field between two FM layers ($H_{\text{ex}}$) ($J = tH_{\text{ex}}M_s$).

If the exchange biased field between PFM and AFM layers is strong enough, the angle between magnetization and easy axis direction of the pinned layer will be fixed at low applied magnetic fields, i.e. $\theta_p$ equals to zero. This can be applied for the present case, where the magnetization reversal of the free and pinned layers occurred separately (see figure 2a).

For small angles, $\cos \theta \approx 1$, the PHE voltage exhibits linear characteristics as well as high sensitivity in low fields ($H < 10 \text{ Oe}$). In this case, the sensitivity of the sensor is given as:

$$S = \frac{V_y}{H_y} = \frac{\Delta R}{H_K + H_{\text{ex}}}. $$  

(3)

Applying this theoretical approach to experimental data, we can determine the values for $H_K, H_{\text{ex}}$ fields and the sensor sensitivity $S$. The obtained results are summarized in table 1 (in brackets). Note that the values of $S$ and $H_{\text{ex}}$ obtained for the fit of the PHE data are in excellent agreement with those derived from experimental data. The values of $H_K$, however, are systematically larger than those obtained from the VSM measurements.

**Figure 2.** Hysteresis loops (a) and low field $V_{\text{PHE}}(H)$ characteristics (b) of spin-valve structures with the fixed pinned layer thickness $t_p = 3 \text{ nm}$ and free layer thickness ($t_f$) varying from 4 to 20 nm. The inserted figures are anisotropy field and sensor sensitivity extracted from experimental data, respectively.
Table 1. Experimental and calculated (in brackets) anisotropy ($H_K$), exchange coupling field ($H_{ex}$) and sensor sensitivity ($S$) for spin-valve system with different free layer thicknesses.

| $t_f$ (nm) | $S$ (mΩ/Oe) | $H_K$ (Oe) | $H_{ex}$ (Oe) |
|-----------|-------------|-----------|-------------|
| 4         | 1.7 (3.5)   | 2 (2.1)   | 5.4 (5.4)   |
| 8         | 4.1 (4.6)   | 2.4 (6.7) | 7.9 (7.9)   |
| 10        | 5.2 (5.5)   | 2.5 (5.5) | 7.7 (7.7)   |
| 15        | 6.1 (6.5)   | 3.5 (5.3) | 7.1 (7.1)   |
| 20        | 7.6 (7.6)   | 3.5 (5.3) | 7.1 (7.1)   |

3.2. Fixed free layer thickness system

Figure 3a presents magnetization data of Ta(5 nm)/NiFe(10 nm)/Cu(1.2 nm)/NiFe($t_p$ nm)/IrMn(15 nm)/Ta(5 nm) spin-valve structures with different pinned layer thickness ($t_p$) from 2 to 12 nm. Here, all samples exhibit two hysteresis loops too. However, contrary to the fixed pinned layer thickness system, the magnetization accounting from the first loop is almost constant while that from the second loop increases with increasing $t_p$. The values of the anisotropy ($H_K$) and exchange coupling ($H_{ex}$) fields determined from these magnetization data are collected and listed in table 2. Note that $H_K$ and $H_{ex}$ increase with increasing $t_p$.

Shown in figure 3b is the sensor voltage as a function of the applied fields. For this fixed pinned layer spin-valve system, it is clear that with increasing $t_p$, the maximal value of the PHE voltage decreases. In addition, this peak shifts to higher magnetic fields. Consequently, the sensor sensitivity $S$ is reduced strongly from 8.8 mΩ/Oe to 3.4 mΩ/Oe when $t_p$ increases from 2 nm to 12 nm (figure 3a, insert).

![Figure 3. Hysteresis loops (a) and low-field $V_{PHE}(H)$ characteristics (b) measured in spin-valve structures with the fixed free layer thickness $x = 10$ nm and different pinned layer thickness ($x$) from 2 to 12 nm.](image)

Calculated values of anisotropy ($H_K$), exchange coupling field ($H_{ex}$) and sensor sensitivity ($S$) are listed in table 2 for the fixed pinned layer thickness spin-valve system. Again, an excellent consistence with experimental results is obtained for $H_{ex}$ and $S$ only.
Table 2. Experimental and calculated (in brackets) anisotropy ($H_K$), exchange coupling field ($H_{ex}$) and sensor sensitivity ($S$) for spin-valve system with different pinned layer thicknesses.

| $t_p$ (nm) | $S$ (m$\Omega$/Oe) | $H_K$ (Oe) | $H_{ex}$ (Oe) |
|-----------|-----------------|--------|--------|
| 2         | 8.8 (8.9)       | 1.2 (2.1) | 10.3 (10.3) |
| 3         | 5.4 (5.9)       | 0.9 (2.9) | 14.4 (14.4) |
| 6         | 3.7 (3.8)       | 1.3 (4.4) | 19.0 (19.0) |
| 9         | 3.3 (3.3)       | 0.6 (2.5) | 22.9 (22.9) |
| 12        | 3.4 (3.3)       | 1.3 (1.2) | 25 (25.0)   |

3.3. Optimal spin-valve configuration for PHE sensor sensitivity

It was provided from above mentioned investigation that the large PHE sensor sensitivity can be reached in spin-valve structures with thin PFM and thick FFM layers. This may relate to the spin collinear structure in the ferromagnetic layers. In the PFM layer, the well-aligned spin part is usually formed near PFM/AFM interface. Further increasing the pinned layer thickness will lead to an enlarging the twisted structure where the magnetization is pinned in different directions from the easy axis (i.e. $\theta_p \neq 0$) [7-10]. In this context, the twisted part can be assumed to be eliminated in the structure with thin pinned layer $t_p = 2$ nm. Practically, the maximal PHE voltage and the highest sensitivity of sensor were observed in this configuration. For the free layers, the magnetic influence and then the twisted part can be established near NM/FFM interface only. The thick free layers thus dominate the collinear ferromagnetic part and enhance the PHE voltage. Combining these two optimal tendencies, we prepared Ta(5 nm)/NiFe(20 nm)/Cu(1.2 nm)/NiFe(2 nm)/IrMn(15 nm)/Ta(5 nm) spin-valve structure, i.e. with $t_f = 20$ nm and $t_p = 2$ nm. Its magnetization and PHE data are presented in figure 4. It is interesting to note that this spin-valve configuration shows sensor sensitivity as large as 15.6 m$\Omega$/Oe.

Figure 4. Hysteresis loops (a) and low-field $V_{PHE}(H)$ characteristics (b) measured in Ta(5 nm)/NiFe(20 nm)/Cu(1.2 nm)/NiFe(2 nm)/IrMn(15 nm)/Ta(5 nm) spin-valve structure, i.e. with $t_f = 20$ nm and $t_p = 2$ nm.
Conclusion remarks
The influence of the individual free and pinned layer thickness to the sensitivity of PHE sensor based on the spin-valve structure of NiFe($t_f$)/Cu(1.2nm)/NiFe($t_p$)/IrMn(15nm) with the size of 50 × 50 μm$^2$ has been studied. The results show that the thicker free ferromagnetic layers enhance the PHE signal, whereas the thicker pinned ferromagnetic layers lower PHE one. For a good combination, the highest PHE sensitivity of 15.6 mΩ/Oe is obtained in the spin-valve configuration with $t_f = 20$ nm and $t_p = 2$ nm. The result is rather promising for application of micro magnetic bead detections in the biology field.

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