High-sensitivity planar Hall sensor based on simple giant magneto resistance NiFe/Cu/NiFe structure for biochip application

Dinh Tu Bui\textsuperscript{1}, Mau Danh Tran\textsuperscript{1}, Huu Duc Nguyen\textsuperscript{1,2} and Hai Binh Nguyen\textsuperscript{3}

\textsuperscript{1} Department of Nano Magnetic Materials and Devices, University of Engineering and Technology, Vietnam National University in Hanoi, 144 Xuan Thuy Road, Hanoi, Vietnam
\textsuperscript{2} Laboratory for Micro and Nano Technology, University of Engineering and Technology, Vietnam National University in Hanoi, 144 Xuan Thuy Road, Hanoi, Vietnam
\textsuperscript{3} Institute of Materials Science, Vietnam Academy of Science and Technology, 18 Hoang Quoc Viet Road, Hanoi, Vietnam

E-mail: buidinhhtu@vnu.edu.vn

Received 7 September 2012
Accepted for publication 14 January 2013
Published 7 February 2013
Online at stacks.iop.org/ANSN/4/015017

Abstract

The planar Hall effect (PHE) sensor based on a simple giant magneto resistance (GMR) trilayer structure NiFe/Cu/NiFe has been designed and fabricated successfully using conventional clean room fabrication methods. The PHE sensor is integrated by 24 sensor patterns with dimensions of $50 \times 50 \mu m$. Influence of individual layer thickness to sensitivity of sensor has been investigated. Sensitivity and planar Hall voltage increases with the decrease of Cu-layer thickness. The results are discussed in terms of the reinforcement of the antiferromagnetic interaction between NiFe layers and shunting current through the layer Cu. The optimum configuration has been found in the structure with the Cu-layer of 1 nm. In this case a single planar Hall effect sensor exhibits a high sensitivity of about $8 \mu V Oe^{-1}$ and a maximal of the signal change as large as $\Delta V \sim 55 \mu V$. These values are comparable to those of the typical PHE sensor based on complex GMR spin-valve structure. With a high sensitivity and simple structure, this sensor is very promising for practical detection of magnetic beads and identifying multiple biological agents in the environment.

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

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

1. Introduction

About two decades ago the discovery of antiferromagnetic interlayer coupling in metallic Fe/Cr-multilayers \cite{1} triggered an enormous research activity in the area of magnetic thin films. It has been experimentally found \cite{2, 3} that depending on the thickness of the non-ferromagnetic layers, e.g. Cr, Cu, Ag or Ru, the magnetic moments of adjacent ferromagnetic layers are spontaneously aligned antiferromagnetically. The underlying oscillatory exchange interaction between the magnetic layers mediated by the nonmagnetic spacer layers has subsequently been identified as a Ruderman–Kittel–Kasuya–Yosida (RKKY)-like interaction between two thin magnetic sheets embedded in a free electron gas \cite{4}. The alignment of the magnetization in the ferromagnetic layers of the multilayer stack strongly influences the resistance of the system. Usually the resistance in the antiferromagnetic state is much higher than in the parallel state at magnetic saturation. This effect, called giant magneto resistance (GMR), is caused by spin-dependent
scattering of the conduction electrons in the magnetic layer and a change in the relative band structure during the magnetization process. The GMR multilayers have already found their way into automotive sensor technology and into leading-edge hard disk drive products, as they can be engineered to be more sensitive to very small magnetic fields than all conventional ferromagnetic metals known. In addition GMR based sensors show an outstanding signal-to-noise ratio. Today, the magnetic label detection is usually accompanied by using giant magnetoresistance effect, planar Hall effect, as well as magnetic tunneling junctions. Among them, planar Hall effect (PHE) has recently received great attention for spintronic biosensor design thanks to its nano-tesla sensitivity and high signal-to-noise ratio [5–9]. PHE is based on the anisotropy magnetoresistance (AMR) of ferromagnetic (FM) materials. The transverse voltage on a planar Hall cross depends on the orientation of the magnetization of the ferromagnetic (FM) 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 a unidirectional anisotropy. For this purpose, Ejsing et al [10,11] have reported a single PHE sensor of NiFe/IrMn/NiFe. Recently, Volmer and Neamtu [12] have reported that thin films of Ni80Fe20 (permalloy) and structures as Ni80Fe20/Cu/Ni80Fe20 were used to build high-sensitivity magnetic field sensors (they used the Wheatstone bridge configuration), Chui et al [13] have demonstrated the detection of pseudo-magnetic beads placed on top of 4×4 and 5×5 μm² planar Hall trilayer (Si/Co 10 nm/Cu 2 nm/NiFe 10 nm) sensors.

The present paper deals with studies of the sensitivity dependence on the thickness of the Cu non-magnetic layer in patterned 50×50 μm² PHE sensor based on Ta/NiFe/Cu/NiFe/Ta GMR structure. This PHE sensor has been proposed to apply for magnetic bead detection.

2. Experimental

GMR Ta(5 nm)/NiFe(5 nm)/Cu(x)/NiFe(2 nm)/Ta(5 nm) structures (with x = 1, 2, 3 nm) are fabricated by dc magnetron sputtering system with the base pressure less than 1.7×10⁻⁷ Torr. The spin-valve structures are sputtered on SiO₂ wafer at room temperature with Argon working pressure of 3×10⁻³ Torr. During sputtering process, a uniform magnetic field of H₀ = 800 Oe is applied in plane of the films, parallel to the Oy direction. This magnetic field induces a magnetic anisotropy in the ferromagnetic (FM) layers.

The PHE sensors are structured by using lithography technique into four-electrode bars with the patterned size of 50 × 50 μm² (figure 1(a)). The bead array counter (BARC) microchip was fabricated by integrating 24 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 Hₓ up to 60 Oe applied along Oy direction and sensing currents Iₓ of 1 mA. Magnetization is measured by means of a Lakeshore 7400 vibrating sample magnetometer (VSM) on defined 12×12 mm² films.

3. Results and discussion

Figure 2 presents the magnetization data of GMR Ta(5)/NiFe(5)/Cu(x)/NiFe(2)/Ta(5) (nm) structures with different spacer layer (Cu) thicknesses (x) varying from 1 to 3 nm. The magnetization rotation in two feromagnetic (FM) layers starts rather early in the thin spacer (Cu) layer thickness samples and later in the thick spacer (Cu) layer thickness samples. However, the final parallel configuration of individual layer magnetizations seems to be completed at the same magnetic field of H = 10 Oe for all samples. In addition, the magnetization reversal was a coherent rotation when the thin spacer (Cu) layer thickness is 1 nm and incoherent when the thin spacer (Cu) layer thickness is 3 nm as shown in figure 2.

Shown in figure 3 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, reaches a maximal value at H ~ 8 Oe and finally decreases with further increase of the magnetic fields. For this GMR system, the maximal value of the PHE voltage increases with decreasing of non-magnetic layer thickness. It increases from the value of 1 μV for sample with x = 3 nm to the value of 55 μV for x = 1 nm.
Oy parallel to the single domain model \( t \) magnetization, respectively, from 1 to 3 nm. Magnetic hysteresis loops of GMR structures with the fixed FM layer thickness and non-magnetic layer thickness varying \( t \) 1 varying from 1 to 3 nm.

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:

\[
V_y = I_x \Delta R \sin \theta \cos \theta, \tag{1}
\]

where \( \Delta R = (\rho_1 - \rho_2) / t \) with \( \rho_1 \) and \( \rho_2 \) are the resistivity measured with the current parallel and perpendicular to the magnetization, respectively, \( t \) is the two ferromagnetic layers thickness.

Typically, these \( V_{\text{PHE}}(H) \) curves are fitted well by using the single domain model [14, 15] with the magnetic energy per unit of the magnetic layer. When a magnetic field \( H_y \) is applied along the \( y \)-axis, the magnetization direction rotates by an angle \( \alpha \) with respect to the \( x \)-axis. This angle can be obtained by minimizing the energy density \( w \). In this case, the Stoner–Wohlfarth energy can be expressed as

\[
w = K_u t_1 \sin^2 \theta_1 - M_s t_1 H \cos(\alpha - \theta_1) + K_u t_2 \sin^2 \theta_2 - M_s t_2 H \cos(\alpha - \theta_2) - J \cos(\theta_1 - \theta_2), \tag{2}
\]

Here, the \( \theta_1 \) and \( \theta_2 \) are the angles between magnetization of the ferromagnetic 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 ferromagnetic layer and \( J \) is the interlayer coupling constant that can be extracted from the relation with the exchange coupling field between two FM layers \( (H_{ex}) \)

\[
(\alpha - H_{ex} M_s). \tag{3}
\]

The increase of the sensitivity in these sensor junctions is usually explained simply by the shunting current in the GMR thin films [15, 16]. When the non-magnetic layer is thicker, the shunting current from other layers is smaller. By reducing the thickness of this layer, the shunting current can increase through remaining layers, leading to the observed higher sensitivity of our PHE sensors.

In addition, the PHE or AMR ratio is relatively sensitive to the mutual alignment of the FM layers [16]. This finding is comparable with the magnetization data mentioned in figure 3. The rotation mutual alignment of the magnetization in the FM layers is well evidenced in the PHE voltage. When the non-magnetic layers (Cu) are thin, then the rotational mutual alignment of the magnetization in the FM layers starts rather early. This is the reason leading to the observed higher sensitivity of our PHE sensors.

4. Conclusion

The influence of the individual non-magnetic layer thickness in the sensitivity of PHE sensor based on the spin-valve structure of NiFe(5)/Cu(x)/NiFe(2) nm with size of 50 × 50 \( \mu \)m\(^2\) has been studied. The results show that the thinner Cu non-magnetic layers enhance the PHE signal, whereas the thicker Cu non-magnetic layers lower PHE one. For a good combination, the highest PHE voltage of 55 \( \mu \)V is obtained in the GMR configuration with \( x = 1 \) nm. The result is rather promising for applying to micro magnetic bead detections in biology field.

Acknowledgment

This work is supported by the research project no. CN.12.09 granted by Vietnam National University, Hanoi.

| Thickness of Cu layer (nm) | \( \Delta V (\mu \text{V}) \) | \( S (\mu \text{V Oe})^{-1} \) |
|---------------------------|-----------------|-----------------|
| 1                         | 55              | 8               |
| 2                         | 8               | 0.74            |
| 3                         | 1               | 0.04            |

Table 1. The sensitivities \( S \) with different Cu thicknesses calculated from equation (3).

Adv. Nat. Sci.: Nanosci. Nanotechnol. 4 (2013) 015017 D T Bui et al
References

[1] Grunberg P, Schreiber R, Pang Y, Brodsky M B and Sowers H 1986 Phys. Rev. Lett. 57 2442
[2] Baibich M N, Broto J M, Fert A, Nguyen F V D, Petroff P, Etienne P, Creuzet G, Friederich A and Chazelas J 1988 Phys. Rev. Lett. 61 2472
[3] Parkin S S P, More N and Roche K P 1990 Phys. Rev. Lett. 64 2304
[4] Coehoorn R 1991 Phys. Rev. B 44 9331
[5] Maekawa S 2006 Concepts in Spin Electronics (Oxford: Oxford Science Publications)
[6] Johnson M 2004 Magnetoelectronics (Amsterdam: Elsevier)
[7] Chappert C, Fert A and Nguyen F V D 2007 Nature Mater. 6 813
[8] Schuhl A, Nguyen F V D and Childress J R 1995 Appl. Phys. Lett. 66 2751
[9] Nguyen V D, Schuhl A, Childress J R and Sussiau M 1996 Sensors Actuators A 53 256
[10] Ejsing L, Hansen M F, Menon A K, Ferreira H A, Graham D L and Freitas P P 2004 Appl. Phys. Lett. 84 4729
[11] 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
[12] Volmer M and Neamtu J 2007 J. Magn. Magn. Mater. 316 265
[13] Chui K M, Adeyeye A O and Li M H 2007 J. Magn. Magn. Mater. 310 992
[14] 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
[15] Nguyen T T, Rao B P, Nguyen H D and Kim C G 2007 Phys. Status. Solidi. A 204 4053
[16] 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