Linearity of Giant Hall resistivity versus magnetic field in Fe/Pt/[CoFe/Pt]ₙ/Fe/Pt multilayers

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Abstract: The Giant Hall effect (GHE) material is one of potential effective materials for magnetic sensors. Meanwhile, because of the magnetic hysteresis of the magnetic materials, the linearity of Giant Hall resistivity could be an extremely important factor for industrial application. The Fe(a Å)/Pt(b Å)/[Co₀.₉Fe₀.₁(3 Å)]/Pt(12 Å)/Fe(a Å)/Pt(b Å) magnetic multilayers were fabricated and their linearity of Giant Hall resistivity versus magnetic field was investigated in out-of-plane direction. By choosing the different structures and adjusting the thickness of the sublayers, the perpendicular interface anisotropy and in-plane shape anisotropy in the multilayers can be fine tuned to control the Giant Hall effect behaviors of the films. As an example of middle-magnetic-field sensor application, the Fe(4 Å)/Pt(6 Å)/[Co₀.₉Fe₀.₁(3 Å)]/Pt(12 Å)/Fe(4 Å)/Pt(6 Å) structure was fabricated to show a good linearity of Hall resistivity of 2.2% with a Hall slope of 16 μΩ·cm/T and a magnetic field range of [-160, 160] Oe at room temperature in out-of-plane direction.

1. Introduction

Semiconductor hall effect devices are being widely used for magnetic sensor application, which

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accounts for more than one billion dollars of market supply in the 2009. But there are still factors which limits its further application, such as the high resistivity, low frequency response, high power consumption, poor linearity, and poor thermal robustness. Interestingly, the semiconductor hall devices are rarely used to measure just a magnetic field for its poor linearity[1]. To overcome these demerits, we can use metallic materials instead of semiconductor. But the Hall effect for common metals and alloys is too weak for sensor using. The Giant Hall Effect (GHE) in magnetic metals and alloys, which arises from spin-orbit scattering, is obviously larger than the ordinary one. Some magnetic materials exhibit very large GHE, which makes it almost suitable for hall detectors. Most of the recently research focuses on improving the hall sensitivity of the magnetic materials. The hall slope of Co0.9Fe0.1/Pt multilayers reached up to 545 μΩ·cm/T at room temperature with a low saturation field of about 10 Oe[2]. The hall slope of Cu(Co) nanoparticle film reached 40mΩ cm/T in the field below 40 Oe by aging-induced method[3]. The Hongkong University reported that the saturated hall resistivity of as large as 200 μΩcm at 4 kG in Ni-SiO2 granular films[4]. These make the Giant Hall effect materials a competitive and potential effective material for the magnetic sensors application.

Because of the magnetic hysteresis of the magnetic materials, the linearity could be an extremely important factor for production. In order to get a good linearity of the Giant Hall effect in magnetic multilayers, it is required that the multilayers exhibit a small negative effective perpendicular magnetic anisotropy (K_{eff})[2,5]. It has been demonstrated that we can change the perpendicular magnetic anisotropy (K_{eff}) by adjusting the thickness of the sublayers in the magnetic multilayers[6]. By choosing different structures and adjusting the thickness of the sublayers can fine tune the perpendicular interface anisotropy and the shape anisotropy in the multilayers[5,6]. In this article, our attention focus on the linearity of Giant Hall resistivity dependence on the applied field of the magnetic multilayers, especially, the Fe/Pt/[CoFe/Pt]$_n$/Fe/Pt multilayers.

2. Experimental

The films with the structure of Fe($a$ Å)/Pt($b$ Å)/[Co$_{0.9}$Fe$_{0.1}$($3$ Å)]/Pt($12$ Å)/Fe($a$ Å)/Pt($b$ Å) were deposited on 4 Inch silicon wafers at room temperature by DC magnetron sputtering by a Lesker CMS-18 Sputtering system. Before deposition, the background pressure was better than 6 × 10$^{-8}$ Torr, the sputtering pressure was 5 mTorr. The Co$_{0.9}$Fe$_{0.1}$ sublayers were deposited by co-sputtering with adjustable sputtering power for Co and Fe targets. To avoid the offset hall voltage at zero applied field, a five-pin mask has been used to format a 5-pad magnetic films.

After the disposition, the hall resistivity behavior was tested by a 5-pin method, and the offset hall voltage was eliminated by adjusting the variable résistance parallel to the hall voltage direction. The applied magnetic field was perpendicular to the film plane. Then 1mA current was input to one direction of the films by using a Keithley 2400 source meter, and hall voltage is acquired by a 16-bits differential analog Data-Acquisition (DAQ) card at the direction perpendicular to the current in plane. To filter the random noise, an average algorithm has been introduced here. The root mean square (RMS) noise of the DAQ card is about 20 μV. As is known that, the GHE of magnetic multilayers is characterized by a parameter of hall resistivity ($\rho_{xy}$):
where $V_y$ is the hall voltage, $I_x$ the current, $t$ the thickness of the film.

3. Results and Discussions

The hall resistivity behavior of the structure Fe($a$ Å)/Pt($b$ Å)/[Co$_{0.9}$Fe$_{0.1}$($3$ Å)]/Pt($12$ Å)/Fe($a$ Å)/Pt($b$ Å) with $a = 4$ Å, $b = 16$ Å, 12 Å, 7 Å, 6 Å, 4 Å and $b = 12$ Å, $a = 3$ Å, 4 Å, 5 Å, 6 Å, 8 Å are shown in the figure 1. The Giant Hall resistivity showed approximately linear dependence on the magnetic field applied perpendicular to the film before saturation, but with different hysteresis for the different structures. Then the hall resistivity dependence on the applied field over the best linearity range was fitted by using the least square method to obtain the response of the GHE films on the applied field. Also the linearity $\Delta$ is calculated as below:

$$\Delta = \frac{\Delta Y_{\text{max}}}{Y_{FS}}$$

$\Delta Y_{\text{max}}$ is the maximum error between the test data and the best fitting line. $Y_{FS}$ is the full scale of the best fitting line of $Y$.

To analysis the data in detail, we can get the linearity, hall sensitivity, best linearity range, dynamic range and the saturated hall resistivity. The hall sensitivity $K$ equals to the slope of the best fitting line. The dynamic range is defined as the maximum field before saturation, or the saturation field, the best linearity range is a range over which the hall resistivity vs. applied field has a best linearity for industrial application. The main characteristics of the different samples are listed in tab.1.
Figure 1. The Giant Hall Resistivity behaviors of the structure of Fe(a Å)/Pt(b Å)/[Co0.9Fe0.1(3 Å)/Pt(12 Å)]3/Fe(a Å)/Pt(b Å) in out-of-plane direction.

From figure 1 and table 1, we can find that:
1. Keep the Fe sublayer thickness \( a = 4 \) Å, increase the Pt sublayers thickness \( b \), or keep the Pt sublayer thickness \( b = 12 \) Å, decrease the Fe sublayers thickness \( a \), the saturation field of hall resistivity decreased. At the same time, the hall slope increase similarly. This comes from the increasing ratio of magnetic metal of Fe.
2. Keep the \( a \) as 4 Å, the samples with smaller \( b \) have better linearity, such as the \( b = 4 \) Å, 6 Å, 7 Å have better linearity than the 12 Å, 16 Å samples. While keep the \( b \) as 12 Å, the samples with larger \( a \) have better linearity, such as \( a = 5 \) Å, 6 Å, 8 Å have better linearity than \( a = 3 \) Å, 4 Å samples.
3. The Fe(4 Å)/Pt(6 Å)/[Co0.9Fe0.1(3 Å)/Pt(12 Å)]3/Fe(4 Å)/Pt(6 Å) multilayers has a best linearity, which reaches to 2.2% over the applied field range of [-160, 160] Oe without any compensation. It makes the material attractive for industrial application on magnetic sensors.
4. Keep the Pt sublayer thickness \( b \) as 12 Å, the saturated hall resistivity increased obviously with the increasing Fe sublayers thickness from 3 Å to 8 Å, which may come from the increasing ratio of magnetic metal of Fe.

Table 1. The main characteristics of the structure Fe(a Å)/Pt(b Å)/[CoFe(3 Å)/Pt(12 Å)]3/Fe(a Å)/Pt(b Å) with different sublayer thickness of \( a \) and \( b \).

| Structure: \( a, b \) (Å) | Linearity \( \Delta \) (%) | Sensitivity \( K \) (μΩcm/T) | Best Linearity Range (Oe) | Dynamic range (Oe) | Saturated Hall Resistivity (μΩcm) |
|---------------------------|--------------------------|-----------------------------|---------------------------|-------------------|-------------------------------|
| \( b = 16 \) | Nonlinearity | 91 | Nonlinearity | [-30, 30] | [-0.17, 0.17] |
| \( b = 12 \) | 15.5% | 178 | [-15, 15] | [-40, 40] | [-0.38, 0.38] |
| \( b = 7 \) | 3.8% | 55 | [-100, 100] | [-200, 200] | [-0.75, 0.75] |
| \( b = 6 \) | 2.2% | 16 | [-160, 160] | [-300, 300] | [-0.32, 0.32] |
| \( b = 4 \) | 6.0% | 35 | [-140, 140] | [-300, 300] | [-0.75, 0.75] |
| \( a = 4 \) | Nonlinearity | 133 | Nonlinearity | [-20, 20] | [-0.22, 0.22] |
| \( a = 5 \) | 15.5 | 178 | [-15, 15] | [-40, 40] | [-0.38, 0.38] |
| \( a = 6 \) | 9.7% | 164 | [-30, 30] | [-50, 50] | [-0.55, 0.55] |
| \( a = 8 \) | 10.9% | 46 | [-120, 120] | [-200, 200] | [-0.65, 0.65] |
| \( b = 12 \) | 5.1% | 19 | [-350, 350] | [-600, 600] | [-0.91, 0.91] |

4. Conclusion
The effective perpendicular magnetic anisotropy of the Fe(a Å)/Pt(b Å)/[CoFe(3 Å)/Pt(12 Å)]3/Fe(a Å)/Pt(b Å) multilayers was tuned by adjusting the thickness of the Fe and Pt sublayers to improve the linearity of Hall resistivity versus applied magnetic field along out-of-plane direction. Meanwhile, the hall resistivity behavior, including the saturation field, the saturation hall resistivity,
and the linearity, can also be controlled to fulfill the specified requirements of certain applications. As an example, the Fe(4 Å)/Pt(6 Å)/[Co0.9Fe0.1(3 Å)/Pt(12 Å)]3/Fe(4 Å)/Pt(6 Å) multilayers showed best linearity of Hall resistivity vs applied magnetic field in perpendicular direction, which reached to 2.2% over the applied field range of [-160, 160] Oe without any compensation. This structure has high possibility on industrial application as a middle-magnetic-field sensor.

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