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Spin valves with Conetic based synthetic ferrimagnet free layer

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ABSTRACT

The detection of low magnetic field requires hysteresis-free magnetoresistive sensor with high sensitivity. Giant magnetoresistance spin valve (SV) sensors with CoFeB based synthetic antiferromagnetic (SAF) pinned layer and Conetic based synthetic ferrimagnet (SF) free layer are developed in this paper. Low free layer coercivity (H_C) of 0.27 Oe is achieved through adapting synthetic antiferromagnetic pinned layer in SV with Conetic single free layer. In SV with SAF pinned layer and SF free layer, the MR ratio, H_C, switching field (H_{SW}) and offset field (H_O) increase with the thickness of the Conetic alloy layer right above the Cu spacer. The H_C, H_O, and H_{SW} show oscillatory behavior with the Ru spacer thickness in the SF free layer. Through introducing CoFeB/SF free layer, an increased sensitivity of 0.27%/Oe and a small coercivity of 0.3 Oe are attained, which holds promise for low field sensing applications.

1. Introduction

Magnetic field sensor with high sensitivity in low field regime is required for detection of nanomagnetism such as magnetic nanoparticles [1–3]. Giant magnetoresistance (GMR) and tunneling magnetoresistance (TMR) sensors are promising candidates for this application. Although generally the magnetoresistance (MR) ratio of TMR sensor is higher [4], GMR sensor has the advantages of exhibiting relatively low noise level [5]. Reducing the switching field (H_{SW}) and increasing the MR ratio of the GMR sensor are two important engineering issues to enhance the sensitivity. Besides, reducing the coercivity (H_C) of the sensor is important to eliminate noise in it [6].

One approach to reduce the H_{SW} and H_C of GMR spin valve (SV) is to use soft magnetic materials as the free layer. Conetic alloy ($Ni_{77}Fe_{14}Cu_5Mo_4$) is a kind of mu-metal. It possesses softer magnetism than the commonly used permalloy (NiFe). The coercivity (H_C) of Conetic alloy is 75% of that of NiFe in the thickness range of 3–10 nm for Ta buffered thin film [7]. Therefore, it can be used as the free layer of SV to reduce the H_{SW}. A low H_{SW} of 3.5 Oe (1 Oe = 79.577 A/m) and MR ratio of 0.4% was reported in a SV with Conetic single free layer [8].

Another way to lessen the H_{SW} and H_C of SV free layer is by incorporating synthetic antiferromagnetic (SAF) pinned layer. An impediment to the use of Conetic alloy as free layer of SV is that a non-uniform magnetic environment in the soft free layer is produced by the stray field from the pinned layer, causing the soft layer to stiffen [9]. Using SAF pinned layer instead of conventional pinned layer is a solution to this problem because there is a cancellation effect of the ripple stray fields. The stray field from the pinned layer can be reduced by 90% [10]. Besides, another advantage is a large pinning field can be induced and thus a better magnetic stability of SV can be achieved [11].

An alternative to reach low H_{SW} and H_C is to reduce the thickness of the free layer. However, the reduction of physical thickness is accompanied by the drop of MR ratio [12]. The effective thickness of the free layer of SV can be reduced while keeping the physical thickness by using a synthetic ferrimagnet (SF) free layer. NiFe based SF free layer was proven to be able to reduce H_{SW} without a significant signal loss in SVs [13,14]. Nevertheless, to the best of our knowledge, the performance of SVs with Conetic based SF free layer is not yet reported.

A major problem of SV with Conetic single free layer is the low MR ratio of it [8]. One possible solution for this problem is to insert a second thin layer of ferromagnetic (FM) material between the free layer and Cu spacer. A thin layer of Co insertion between the spacer and the NiFe FM layers was demonstrated to be an effective method to enhance the MR ratio of SV [15]. Similar structures with a thin layer of CoFe or CoFeB insertion between Cu spacer and NiFe free layer have also been used in a previous study to fabricate SV with

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high MR ratio [16].

In this paper, we developed SVs with CoFeB based SAF pinned layer and Conetic based SF free layer. Reduced H_C and enhanced sensitivity are demonstrated in this structure. In the first part of our experiment, the effect of adopting SAF pinned layer is investigated by comparing the MR curve in low field range and M-H loop of SV with SAF pinned layer to the conventional SV. In the second part, the thickness of the Conetic alloy layer right above the Cu spacer is varied to investigate how the FM layer thickness of the SF free layer affects the performance of the SV. The Ru spacer thickness in the SF free layer is further optimized to reduce H_C. In the last part, the MR ratio of the SV is enhanced by inserting a 0.5 nm CoFeB thin layer between the Cu spacer and the SF free layer.

2. Experiment

SV films were prepared by DC magnetron sputtering with a base pressure of 12×10^{-7} Pa. The Ar pressure of samples deposition was 0.4–0.67 Pa. The layer stacks of the four groups of samples prepared are listed in Table 1 below. The detailed structure diagrams of the four groups of samples are shown in Fig. 1. The sputtering rates of different materials were calibrated by atomic force microscopy. Firstly, conventional SV (sample group 1) and SV with SAF pinned layer (sample group 2) were prepared and the performance was compared. Later, SVs with SAF pinned layer and SF free layer (sample group 3) were prepared. In the investigation on FM layer thickness dependence, the thickness of the Conetic alloy layer right above the Cu spacer (t_{P1}) of sample group 3(a) was varied from 3.5 nm to 7 nm while keeping t_{Ru} at 0.7 nm. The thickness of the Ru spacer in the SF free layer (t_{Ru}) of sample group 3(b) was varied from 0.5 nm to 1.1 nm while keeping $t_{P1} = 6$ nm to define an optimal t_{Ru} for low H_C. The deposition rate of Ru was set at a very slow rate ~0.6 nm/min so that t_{Ru} was controlled with a high resolution. Finally, SV with SAF pinned layer and CoFeB/Conetic SF free layer (sample group 4) was prepared to explore the effect of inserting CoFeB in the free layer. Current-in-plane GMR measurements were carried out with a standard four probe system. H_{SW} is defined as half of the difference of the fields at the two points that the SV resistance reached 90% of full resistance change [17]. Magnetization measurements were carried out using a vibrating sample magnetometer (VSM).

3. Results and discussion

The SAF pinned layer is introduced as a possible approach to reduce H_{SW} and H_C. The MR curves in low field range of sample group 1 and 2 are compared, as shown in Fig. 2. A drop of MR ratio from 0.22% to 0.13% is observed after using SAF pinned layer. Nonetheless, a 91% reduction in H_C (from 3 Oe to 0.27 Oe) and 77% decrease in H_{SW} (from 7 Oe to 1.6 Oe) are observed. This has resulted in a 150% improvement in sensitivity from 0.016%/Oe to 0.04%/Oe. The reason behind the drop of H_{SW} and H_C is that the stray field originated from magnetic ripple in the pinned layer stiffening the soft free layer is mitigated through adopting SAF pinned layer [9,10]. The M-H loops of sample group 1 and 2 are shown in Fig. 3. The VSM results show that the reference layer and free layer hysteresis loops of sample group 1 are well separated while there is some overlapping for sample group 2. That indicates the pinning field is increased and the coupling between the free

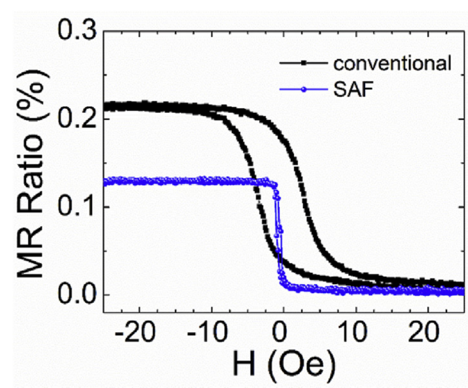

Fig. 2. MR curves in low field range of sample group 1 and 2.

Table 1
Layer structures of sample group 1–4.

Sample group	Description	Structure (thickness in nanometer)
1	Conventional SV	Ru 3.5/IrMn 5.5/CoFeB 3.5/Cu 6.5/$Ni_{77}Fe_{14}Cu_5Mo_4$ 6/Ru 3.5
2	SV with SAF pinned layer	Ru 3.5/IrMn 5.5/CoFeB 2/Ru 0.7/CoFeB 2/Cu 6.5/$Ni_{77}Fe_{14}Cu_5Mo_4$ 6/Ru 3.5
3(a)	SV with SAF pinned layer and SF free layer	Ru 3.5/IrMn 5.5/CoFeB 2/Ru 0.7/CoFeB 2/Cu 6.5/$Ni_{77}Fe_{14}Cu_5Mo_4$(P1) (t_{P1})/Ru 0.7/$Ni_{77}Fe_{14}Cu_5Mo_4$(P2) 2/Ru 3.5, where t_{P1} = 3.5, 4, 5, 6 and 7
3(b)		Ru 3.5/IrMn 5.5/CoFeB 2/Ru 0.7/CoFeB 2/Cu 6.5/$Ni_{77}Fe_{14}Cu_5Mo_4$(P1) 6/Ru (t_{Ru})/$Ni_{77}Fe_{14}Cu_5Mo_4$(P2) 2/Ru 3.5, where t_{Ru} = 0.5, 0.6, 0.7, 0.8, 0.9, 1 and 1.1
4	SV with SAF pinned layer and CoFeB/Conetic SF free layer	Ru 3.5/IrMn 5.5/CoFeB 2/Ru 0.7/CoFeB 2/Cu 6.5/CoFeB 0.5/$Ni_{77}Fe_{14}Cu_5Mo_4$ 4/Ru 0.7/$Ni_{77}Fe_{14}Cu_5Mo_4$ 2/Ru 3.5

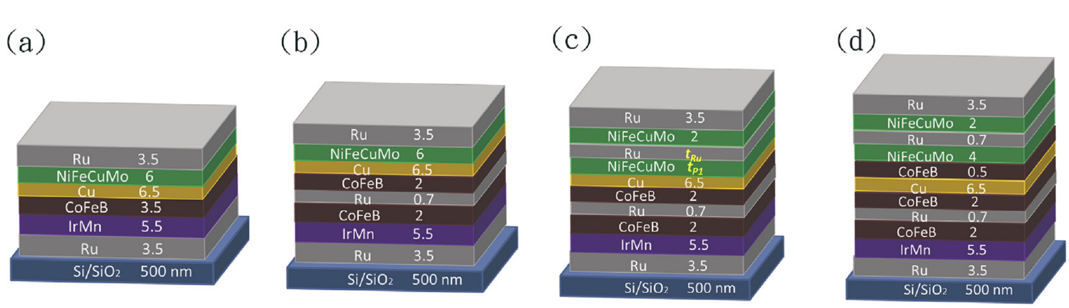

Fig. 1. Schematic of (a) sample group 1, (b) sample group 2, (c) sample group 3 and (d) sample group 4.

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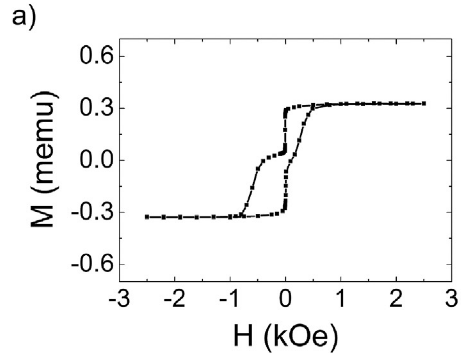

Fig. 3. M-H loops of (a) sample group 1 and (b) sample group 2.

layer and the pinned layer is weakened by adopting SAF pinned layer.

The thickness of P1 Conetic alloy layer (t_{P1}) in sample group 3(a) is varied from 3.5 nm to 7 nm to investigate the FM layer thickness dependence. The MR Ratio, offset field (H_O), H_C, and H_{SW} at different t_{P1} are shown in Fig. 4(a). H_O is defined as the magnitude of the offset field of the center of the MR loop from origin in the x-axis direction. The MR ratio and the three parameters H_C, H_O, and H_{SW} increase with t_{P1}. Here we found that H_C increases with t_{P1}, which is contradictory to the previous studies in CoFe and CoFeB based SF free layer [18,19]. The increase in H_C could be explained by the increase of H_O (which equals to the coupling field between the free layer and pinned layer) when t_{P1} increases [20]. By Neel's "orange peel" model, the surface roughness which increases with t_{P1} is a factor enhancing the coupling field between the reference layer and free layer of SV [21]. Our samples already exhibit an extremely low H_C of 0.05–0.5 Oe, thus the effect of surface roughness (which increase H_C) is very likely to dominate rather than the antiferromagnetic coupling in the SF stack (which decreases H_C). The change in MR ratio and H_{SW} with t_{P1} results in changing sensitivity, as shown in Fig. 4(b). The sensitivity reaches a maximum of 0.13%/Oe when the thickness of the P1 layer equals to 4 nm.

The thickness of the Ru spacer (t_{Ru}) in the SF free layer of sample group 3(b) is further optimized to achieve high sensitivity. The antiferromagnetic (AF) coupling energy was reported to oscillate with t_{Ru}. An AF coupling peak of Co/NiFe/Ru/NiFe stack was found at t_{Ru} ~0.7 nm in a previous study [14]. The MR Ratio, H_O, H_C, and H_{SW} at different t_{Ru} are shown in Fig. 5(a). The MR ratio, H_C, H_O, and H_{SW} oscillate when t_{Ru} increases. The oscillation of H_C, H_{SW} and H_O is possibly due to AF coupling between P1 and P2 layers of the SF free layer [19,20]. The coupling energy of a synthetic ferrimagnet shows an oscillatory behavior when t_{Ru} changes accordingly [19]. As t_{Ru} increases from 0.5 to 0.9 nm, there is a fluctuation of MR ratio between 0.14% and 0.19%. And then there is a sudden drop of MR ratio to 0.1% at $t_{Ru} = 1$ nm, after that the MR ratio increased back to 0.15% for $t_{Ru} = 1.1$ nm. The fluctuation in MR ratio is possibly due to the variation of AF coupling perfectness of the SF stack [11], since the spin-dependent scattering is strongly reliant on the alignment between the free layer and pinned layer. The MR ratios of these SV samples are relatively small thus the effect of coupling between P1 and P2 layer on the MR ratio become more significant. The change in MR ratio and H_{SW} with t_{Ru} results in changing sensitivity, as shown in Fig. 5(b). The sensitivity has a small fluctuation within 0.085–0.105%/Oe for $t_{Ru} = 0.5$–0.9 nm. It drops to a value of 0.06%/Oe at $t_{Ru} = 1$ nm and then increased back to 0.08%/Oe for $t_{Ru} = 1.1$ nm. A minimum H_C of 0.25 Oe is achieved when $t_{Ru} = 0.7$ nm. In the following investigation, this thickness is used in order to achieve low H_C.

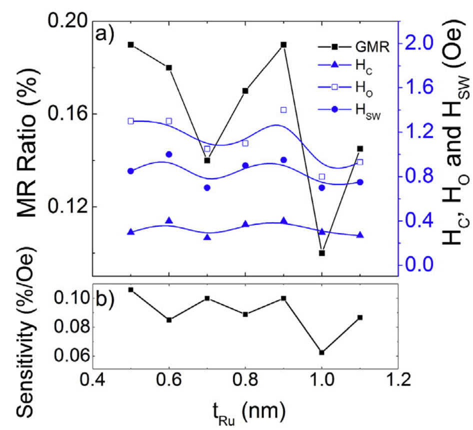

Fig. 5. (a) MR ratio, H_C, H_O, and H_{SW} versus t_{Ru} (fitted curves are used for H_C, H_O, and H_{SW} versus t_{Ru} in order to show the oscillatory behavior due to the AF coupling between P1 and P2 layers) and (b) sensitivity versus t_{Ru} for the SV sample group 3(b).

The above results have shown much smaller H_{SW} and H_C than the previously reported values (a H_{SW} of 3.5 Oe and H_C of 1 Oe using Conetic single free layer [8]) in GMR SVs. Its capability to sense weak magnetic field would be further enhanced if higher MR ratio can be reached. In this investigation, a 0.5 nm CoFeB ultra-thin layer is inserted between the Cu spacer and the SF free layer to explore this effect on MR ratio. CoFeB is chosen as the material of thin layer insertion because it possesses soft magnetism and high spin

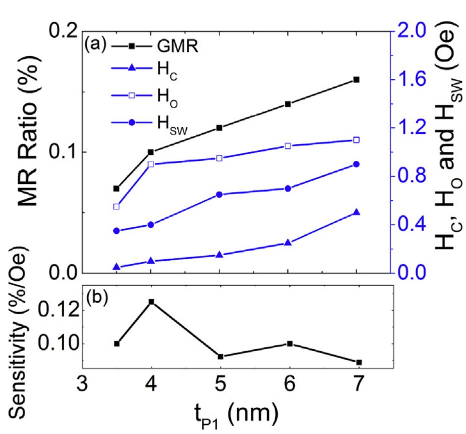

Fig. 4. (a) MR ratio, H_C, H_O and H_{SW} versus t_{P1} and (b) sensitivity versus t_{P1} for the SV sample group 3(a).

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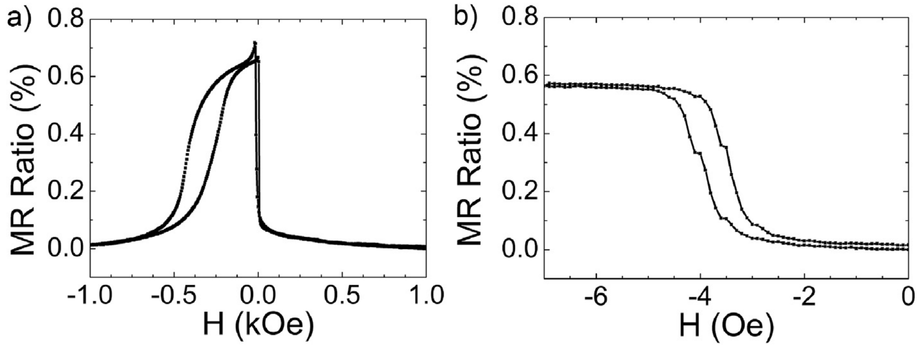

Fig. 6. (a) Full MR curves and (b) MR curves in low field range of the SV with SAF pinned and CoFeB/SF free layer.

polarization [22]. Fig. 6 shows the (a) full MR curve and (b) MR curve in low field range of sample group 4. With the 0.5 nm CoFeB thin layer insertion, the MR ratio of the SV is increased dramatically by six times from 0.1% to 0.6%. The increased MR ratio is attributed to the enhanced spin-dependent scattering at the Cu/CoFeB interface [15]. The Hc, $H_{O,}$ and H_{SW} are increased from 0.1 Oe to 0.3 Oe, 0.9 Oe to 3.3 Oe and 0.4 Oe to 1.1 Oe respectively. These parameters indicate that the SV are sensitive to low magnetic field because the magnetic softness of the amorphous CoFeB. The large enhancement of MR ratio without trading off the low H_{SW} and H_C has resulted in a 108% increase in sensitivity, which is from 0.13 to 0.27%/Oe. These results have shown the CoFeB insertion layer is beneficial for enhancing the performance of the SV with SF free layers.

Sample group 4 shows a sensitivity of 0.27%/Oe, H_{SW} of 1.1 Oe, H_C of 0.3 Oe, and H_O of 3.3 Oe. Although its MR ratio is still lower than the previous study using NiFe based SF free layer (a MR ratio of 6.7% [2]), we have demonstrated much smaller H_C and H_O (cf. a H_C of 2 Oe and H_O of 14 Oe for NiFe based SF SV [2]). This has proven the capability of our sample for low field sensing application. When compared to the previous study using Conetic single free layer, our sample is demonstrating enhanced sensitivity and reduced H_C and H_{SW} (cf. a sensitivity of 0.05%/Oe, H_{SW} of 3.5 Oe and H_C of 1 Oe [8]).

Some future works are anticipated to advance the performance of the sensor. The MR Ratio could be enhanced by adding a nano-oxide layer between the SF free layer and the Ru capping to introduce specular scattering [23,24]. Magnetic thermal annealing is another possible method to further increase the MR ratio of the SV. A critical annealing B-field of 4.5 kOe for the SAF SV was reported [8]. Both of the two methods could lead to a further increase of sensor sensitivity.

4. Conclusion

SVs with CoFeB based SAF pinned layer and Conetic based SF free layer are developed. The introduction of SAF pinned layer results in a remarkable reduction of the H_C and H_{SW} in SV with Conetic single free layer. In SV with SAF pinned layer and SF free layer, the MR ratio and all the three parameters H_C, $H_{O,}$ and H_{SW} increase with t_{P1}, and Ru = 0.7 nm is a suitable choice for SV for its low H_C of 0.25 Oe. A sensitivity of 0.27%/Oe and low H_C of 0.3 Oe is achieved by using CoFeB/SF free layer. Our results have shown enhanced sensitivity and reduced H_C, $H_{SW,}$ and H_O. The high sensitivity and the low H_C, H_{SW}, and H_O of the SV with Conetic based SF free layer have proven its great potential for detection of low magnetic field.

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