Hysteresis-Free Spin Valves for GMR Sensors

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ABSTRACT

Top spin valves of composition Ta/[FeNi/CoFe]/Cu/CoFe/(FeMn, MnIr)/Ta with two types of antiferromagnetic layers ($Fe_{50}Mn_{50}$ or $Mn_{75}Ir_{25}$) were prepared by DC magnetron sputtering. The following three-step procedure was used for the free layer hysteresis reduction: deposition of the composite free layer FeNi/CoFe, optimization of magnetic and nonmagnetic layer thicknesses and application of "nearly parallel" anisotropy configuration. It is shown that in the spin valves studied the hysteresis can be effectively reduced to a few tenths of an oersted at the magnetoresistance higher than 8%.

Keywords: spin valve, giant magnetoresistance, composite free layer, hysteresis.

1 INTRODUCTION

Magnetic nanostructures of "spin valve" (SV) type demonstrating giant magnetoresistance (GMR) and tunnel magnetoresistance (TMR) are the basic elements for spintronics devices. The main feature of an exchange biased SV is high magnetoresistive sensitivity in low magnetic fields. The significant progress in manufacturing multilayers with high TMR ratio has been achieved in the recent few years. An extremely high magnetoresistance was found in spin valves with double MgO barriers [1]. These TMR nanomaterials are useful for various digital applications such as magnetoresistive reading heads, magnetic memory (MRAM), magnetoresistive sensors for "switching" type devices, etc. The presence of magnetic hysteresis of few oersteds caused by the "free layer" magnetization reversal is a typical feature of GMR and TMR materials used in digital applications. However, for analogous applications (magnetic field sensors, current sensors, signal isolator devices, etc.) one must have a material with very low or negligible coercivity. In this case metallic spin valves with GMR effect of about 10 % are preferable [2]. These nanostructures consist of a comparatively small number of magnetic and nonmagnetic layers, and therefore it is possible to reduce the low field hysteresis loop width (free layer coercivity, H_C) down to several oersteds by an adjustment of optimal combination of layer thicknesses.

Several additional methods of the free layer hysteresis reduction have been established in the first years of spin valves studies. The composite free layer FeNi/CoFe appeared to be a soft magnetic material which considerably reduces the coercivity of a top spin valve [3]. The low field coercivity is strongly affected by mutual orientation of three directions in a film plane: the pinning direction (PD) determined by the magnetic field direction during the SV deposition; the easy axis (EA) direction in a free layer and the applied magnetic field (MF) direction in magnetoresistance measurements. The following three cases were previously studied in detail: (a) MF ∥ PD ⊥ EA (crossed configuration); (b) MF ⊥ EA and the PD is deviated by a small angle from the MF direction (nearly crossed configuration) and (c) MF ∥ EA and the PD is deviated by only a small angle from the EA direction (nearly parallel configuration). A comparison of experimental results for these configurations was performed, e.g., in [4]. The maximum magnetoresistive sensitivity at the minimum hysteresis of the free layer corresponds to the nearly parallel configuration [5]. As shown by magneto-optical investigations [6], the physical reason responsible for the decrease of free layer coercivity depending on geometrical factors is the change in the mechanism of magnetization reversal. The magnetization reversal due to displacements of domain walls in the collinear configuration (MF ∥ EA ∥ PD) changes into the magnetization reversal mainly due to the reversible processes of magnetization rotation in case of, e.g., the noncollinear anisotropy configuration.

The main goal of the present study is the experimental investigation of various methods of reducing the free layer hysteresis to the values as small as a few tenths of an oersted for spin valves with GMR ratio higher than 8 %.

2 EXPERIMENT

Ta/[NiFe/CoFe]/Cu/CoFe/(FeMn, MnIr)/Ta spin valves were prepared by dc magnetron sputtering using an MPS-4000-C6 (Ulvac) device onto the (100)Si and Corning glass substrates. The spin valves were deposited at room temperature at an argon pressure of 0.1 Pa and a magnetron power of 100 W. The basic pressure in the sputtering chamber was $P = 6\times10^{-7}$ Pa. Before the SV deposition the substrate surface was cleaned by the reverse magnetron sputtering using an ac magnetron. The deposition rate of each material was determined using a Zygo NewView 7300 optical profilometer from the measurement of the heights of "steps" and the known time of layer deposition. The electrical resistance was measured at room temperature using a standard dc four probe method with CIP geometry. The magnetoresistance was determined as $\Delta R(H)/R = [(R(H)-R_s)/R_s] \times 100\%$, where $R(H)$ is the resistance of a sample in a magnetic field and R_s is the resistance in the field of magnetic saturation. The maximal value of magnetoresistance (GMR ratio) is denoted as MR. The geometry of magnetoresistance measurements is shown in Fig. 1. In this experiment the free layer easy axis is parallel to the pinning direction and perpendicular to the current, and angle α between the free layer easy axis and the magnetic field vector is varied from –20° to +90° in the film plane.

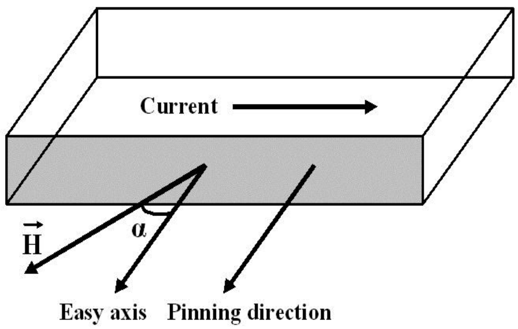

Figure 1: Geometry of magnetoresistance measurements.

3 RESULTS AND DISCUSSION

The total formula of the nanostructure prepared can be written as follows: substrate/Ta(t_{Ta})/NiFe(t_{NiFe})/CoFe(t_{CoFe})/ Cu(t_{Cu})/CoFe(t_{CoFe})/AFM(t_{AFM})/Ta(20 Å), where t_M denotes the thickness of the layer of material M. To optimize the magnetoresistive characteristics, the thicknesses of some layers were varied.

Two antiferromagnetic alloys, $Fe_{50}Mn_{50}$ and $Mn_{75}Ir_{25}$, have been used in these studies. The $Fe_{50}Mn_{50}$ alloy is the simplest antiferromagnetic suitable for investigations of dependences of the spin valve properties on the technological parameters. However, this antiferromagnetic has a low Néel temperature (T_N =217°C), and $Fe_{50}Mn_{50}$-based spin valves have low thermal stability. In this case the blocking temperature T_b, at which the bias effect in a FM/AFM system disappears, is equal to 120–190°C. The $Mn_{75}Ir_{25}$ antiferromagnetic is known to have a significantly higher Néel temperature (T_N = 427°C). The blocking temperature for $Mn_{75}Ir_{25}$-based spin valves is T_b = (250–300)°C.

3.1 $Fe_{50}Mn_{50}$-based Spin Valves

An optimal thickness of $Fe_{50}Mn_{50}$ antiferromagnetic layer is determined as a thickness at which the GMR ratio of Si/Ta(50Å)/NiFe(20Å)/CoFe(55Å)/Cu(24Å)/CoFe(55Å)/ FeMn(t_{FeMn})/Ta(20Å) spin valve is maximal. At various thicknesses of the $Fe_{50}Mn_{50}$ layer, t_{FeMn} = 75, 100, 150, 200, 250 Å, the following values of magnetoresistance (MR) were obtained, MR = 3.8, 7.4, 9.4, 8.3, 7.3%, respectively. For further optimization of the spin valve characteristics the thickness t_{FeMn} = 150 Å was used. The subsequent changes in the thicknesses of Cu layers showed that the maximum sensitivity higher than 6%/Oe is observed for the spin valve with t_{Cu} = 32 Å. The MR = 8.2% and $H_C(0)$ = 14 Oe are observed in this SV. The minimal free layer coercivity of about $H_C(0)$ = 6 Oe and the maximal GMR ratio of 9.4 % are revealed in the spin valve with t_{Cu} = 24 Å. Figure 2 demonstrates field dependences of magnetoresistance of spin valves with two different copper layer thicknesses.

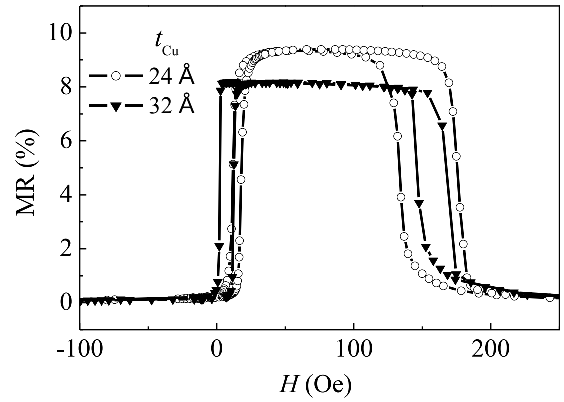

Figure 2: Field dependences of magnetoresistance of the Si/Ta(50Å)/NiFe(20Å)/CoFe(55Å)/Cu(t_{Cu})/CoFe(55Å)/ FeMn(150Å)/Ta(20Å) spin valve.

To reduce the free layer coercivity down to few tenths of oersteds, an anisotropy configuration must be taken into account. It is known that the maximal free layer coercivity can be measured in the collinear anisotropy configuration (MF ‖ EA ‖ PD). It is possible to create the crossed (MF ‖ PD ⊥ EA) or nearly parallel anisotropy configurations *in situ* by deposition of separate layers in the magnetic field applied in different directions. An angle between the free layer easy axis and the pinning direction can be fixed using thermo-magnetic treatment after a SV deposition, as well [6]. As mentioned above, spin valves with noncollinear anisotropy configurations can demonstrate a very low coercivity. We have found that the similar result may be obtained using a simpler way, namely, the rotation of a SV with the fixed collinear orientation of the free layer easy axis and the pinning direction (EA ‖ PD) in a magnetic field (Fig. 1). In this case the thermo-magnetic treatment is excluded from the procedure of the SV preparation, but the low coercivity state can be realized only at some effective angle α. It has been established that the angle α is strongly dependent on the initial free layer coercivity measured in the collinear anisotropy configuration. The dependence of GMR ratio and H_C on the angle α in spin valves with different initial widths of the free layer hysteresis loops is shown in Fig. 3. One can see that $H_C(\alpha)$ tends to zero and nearly vanishes at the angle α = 15° in case of a SV with t_{Cu} = 24Å and $H_C(0)$ = 6 Oe. If the initial free layer coercivity is large, $H_C(0)$ = 14 Oe, as it is in the SV with t_{Cu} = 32 Å, the reduction of H_C down to

$H_C < 1$ Oe occurs at high angles ($\alpha > 40°$) when the GMR ratio and sensitivity decrease considerably. The latter example implies the necessity of previous optimization of spin valve characteristics by variation of magnetic and nonmagnetic layer thicknesses aimed to reduce the free layer coercivity down to lower than $H_C(0) < 10$ Oe. In this case the SV rotation in a magnetic field by a relatively small angle, $\alpha = 10°–15°$, results in a significant decrease of $H_C(\alpha)$.

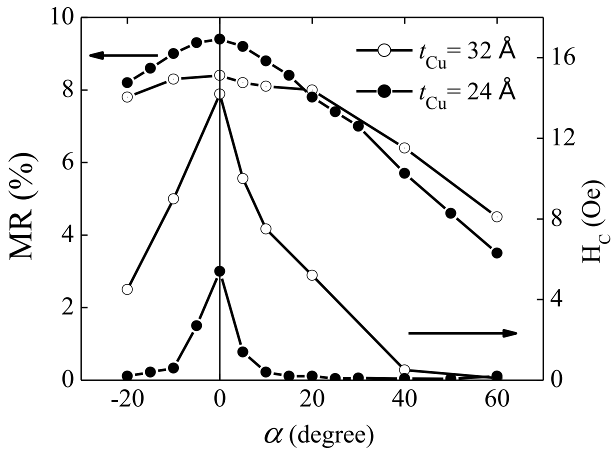

Figure 3: Angular dependences of the GMR ratio and the free layer coercivity for spin valves with two different Cu layer thicknesses (denoted as t_{Cu} in the figure).

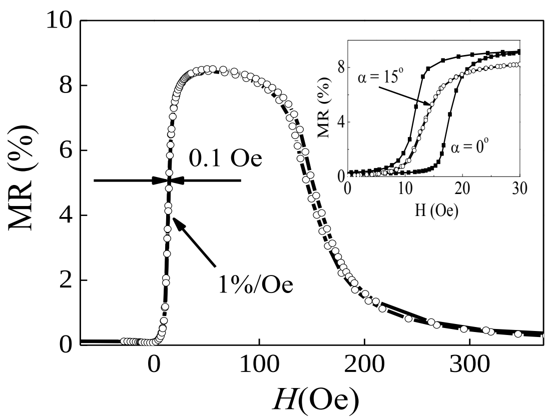

Figure 4: Field dependence of magnetoresistance of the Ta(50Å)/NiFe(20Å)/CoFe(55Å)/Cu(24Å)/CoFe(55Å)/FeMn(150Å)/Ta(20Å) spin valve. The insert shows the low field hysteresis loops for two angles α.

Figure 4 shows the hysteresis-free MR(H) dependence measured in low magnetic fields. The insert in Fig. 4 shows that $H_C(15^o)$ is more than 30 times lower than the free layer coercivity in the parallel anisotropy configuration, $H_C(0) = 6$ Oe and $H_C(15^o) = (0.1 \div 0.2)$ Oe. At the same time, the MR decrease due to the SV turn by 15 degrees is insignificant, from MR = 9.4% at $\alpha = 0°$ to MR = 8.4% at $\alpha = 15°$. The magnetoresistive sensitivity corresponding to the middle of linear part in the hysteresis-less MR(H) curve is ~ 1%/Oe.

3.2 $Mn_{75}Ir_{25}$ -based Spin Valves

The preparation method and composition of the MnIr-based spin valves are similar to those of the FeMn-based spin valves, glass/Ta/NiFe/CoFe/Cu/CoFe/MnIr/Ta, with differences in substrates type, materials of antiferromagnetic (AFM) layer and thicknesses of individual layers. The magnetoresistive properties of the spin valves studied appeared to be nearly independent on the substrate type, glass or (100)Si. In all the MnIr-based spin valves under study the fixed thickness $t_{MnIr} = 50$ Å was used. The following combination of layer thicknesses, glass/Ta(20Å)/NiFe(25Å)/CoFe(20Å)/Cu(24Å)/CoFe(25Å) /MnIr(50Å)/Ta(20Å) has been found optimal as the first step of improving properties of the spin valves. The maximal GMR ratio MR = 11.6 % is revealed for this SV (Fig. 5). One can see that the free layer coercivity measured in the parallel geometry significantly exceeds the H_C measured in the above described FeMn-based spin valves and reaches the value of $H_C(0) = 25.2$ Oe. Figure 5 also demonstrates that the sensitivity increases from 2.5%/Oe to 5.3%/Oe with no change of the GMR ratio upon the turn of this SV in a magnetic field by the high angle (α = 30°), whereas the coercivity remains relatively large, $H_C(30^o) = 9.6$ Oe. To reduce the initial free layer coercivity $H_C(0)$ several spin valves with different thicknesses of NiFe and CoFe (in the composite free layer), Cu and Ta layers were prepared. Modification of the relationship of NiFe and CoFe layer thicknesses in the composite free layer affects the properties of this soft magnetic material and, therefore, changes its coercivity. It has been found that the transition from NiFe(25Å)/CoFe(20Å) to NiFe(30Å)/CoFe(15Å) configuration in this SV leads to the coercivity decrease from $H_C(0) = 25.2$ Oe to $H_C(0) = 17.4$ Oe. The next step in improving the SV characteristics was varying the Cu layer thickness.

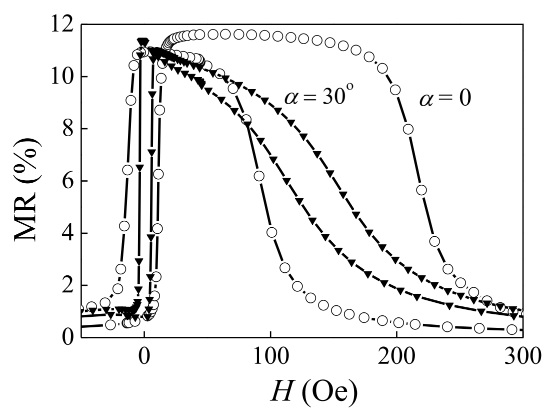

Figure 5: The MR(H) dependences of the glass/Ta(20Å)/NiFe(25Å)/CoFe(20Å)/Cu(24Å)/CoFe(25Å)/MnIr(50Å)/Ta(20 Å) spin valve corresponding to two angles α.

Figure 6 shows the MR(H) dependences for spin valves with t_{Cu} = 24, 22 and 20 Å. One can see that in case of the spin valve with t_{Cu} = 22 Å the free layer coercivity is H_C = 11 Oe at MR = 10.5 %. A further decrease in the Cu layer thickness to t_{Cu} = 20 Å leads to a significant decrease in the sensitivity and the MR magnitude. Note that the MR(H) dependence for the spin valve with t_{Cu} = 22 Å is changed and the sensitivity in small magnetic fields is three times less compared to that in the spin valve with t_{Cu} = 24 Å. To increase the sensitivity we increased the thickness of Ta buffer layer in the SV with t_{Cu} = 22 Å. It is known that the use of tantalum as a buffer layer neighboring the layer of permalloy improves the <111> texture, increases the average grain size in Ta/FeNi layers and decreases the coercivity of the FeNi free layer [7] or FeNi/CoFe composite free layer [3].

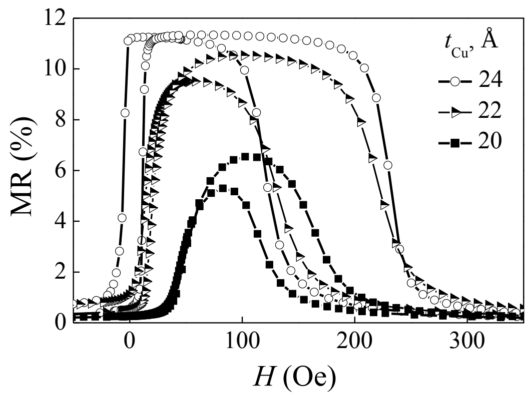

Figure 6: The MR(H) dependences of the glass/Ta(20Å)/ NiFe(30Å)/CoFe(15Å)/Cu(t_{Cu})/CoFe(25Å)/MnIr(50Å)/ Ta(20Å) spin valve for three Cu layer thicknesses.

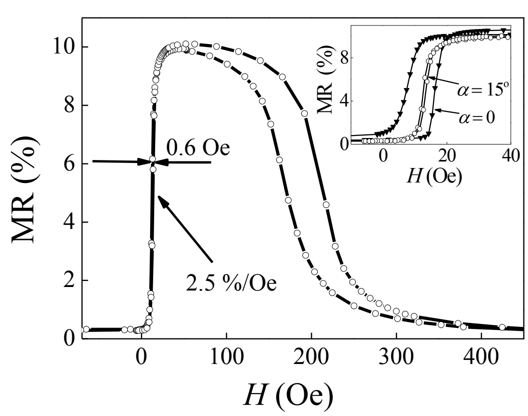

Figure 7: Low-hysteresis MR(H) dependences for the glass/Ta(50Å)/ NiFe(30Å)/CoFe(15Å)/Cu(22Å)/ CoFe(25Å)/MnIr(50Å)/Ta(20Å) spin valve. The inset shows free layer hysteresis loops for two angles α.

When the thickness of Ta buffer layer is increased from 20 to 50 Å, the free layer coercivity decreases from $H_C(0)$ = 11 Oe to $H_C(0)$ = 8.7 Oe, and the sensitivity increases from 0.5 to 1.7%/Oe (the average value for the ascending and descending branches of the hysteresis loop). The resulting (measured at $\alpha = 15°$) MR(H) dependence demonstrates low coercivity $H_C(15^o)$ = 0.6 Oe, high sensitivity of about 2.5%/Oe and MR = 10.5% (see Fig. 7).

4 CONCLUSION

It has been shown that the free layer coercivity of the top spin valve with the composition of Ta/[NiFe/CoFe]/Cu/ CoFe/(FeMn, MnIr)/Ta can be effectively decreased down to a few tenths of an oersted. The GMR ratio above MR = 8 % and sensitivity higher than 1%/Oe have been achieved in the spin valves studied. To obtain these results, three step procedures have been used: (1) deposition of a composite free layer $Ni_{80}Fe_{20}/Co_{90}Fe_{10}$; (2) searching for optimal combination of magnetic and non-magnetic layer thicknesses; and (3) application of the modified nearly parallel anisotropy configuration in which the free layer easy axis is parallel to the pinning direction and the magnetic field is deviated from this direction by a certain angle in the film plane. This geometry permits to exclude other special methods usually used for realization of the noncollinear anisotropy configuration in spin valves. One should emphasize that in our case the hysteresis-less state exists at a certain effective angle α. For an arbitrary angle α the free layer coercivity $H_C(\alpha)$ varies in the interval of $0 \leq H_C(\alpha) \leq H_C(0)$. If the angle α is fixed, as is often the case in modern GMR sensors, the hysteresis-less dependence showed on Figures 4 and 7 can be realized.

5 ACKNOWLEDGMENTS

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