Influence of mechanical strain on magnetic characteristics of spin valves

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Abstract. Giant magnetoresistance (GMR) of Co and Fe-Co based e-beam evaporated spin valves with Cu and Au spacers was studied. The effect of strain on samples, which is detrimental in standard GMR sensors, was measured in a bending configuration. The different dependences of coercivity $H_c$ and magnetic field $H_{ip}$ in the point of inflection of MR loops vs. strain were found. For sample with Co/Au/Co core, $H_c$, $H_{ip}$ increase with increasing compressive stress, whereas for sample with FeCo/Cu/Co core they increase with tensile stress. The highest relative change of MR ratio vs. bending in the strain interval $\pm 300 \times 10^{-6}$ is 1-2 % of the basic magnetoresistance and, practically, it does not influence the SV output.

1. Introduction

The giant magnetoresistance effect (GMR) was discovered nearly 20 years ago in multilayers [1]. Later a simple four-layered spin-valve (SV) structure with two ferromagnetic layers separated by a non-magnetic spacer and one of them pinned by antiferromagnetic layer was introduced [2]. Nowadays GMR-based products are commercially available and research moved into new areas, e.g. combining GMR with magnetostriction. This way sensors of mechanical quantities are produced. Here the magnetization orientation in magnetostrictive material is influenced by stress (strain), i.e. inverse magnetostriction (Villary effect) is effective [3]. SV [3][4], trilayers (pseudo SV) [4][5] or multilayers [6] are studied. However, magnetostriction should be eliminated in high-performance GMR sensors, because it induces undesirable anisotropy of magnetoelastic origin. In [7] magnetostriction in NiFe/Ag multilayer was suppressed by heat treatment at 330 – 360°C. Nevertheless, the heat treatment of SV is not an universal approach to get rid of magnetostriction. Samples should be obtained by proper design and method of deposition. From this point of view in this paper we pay attention to magnetostrictive behaviour of simple Co-based pseudo SV structures (with pinning of one layer due to different coercivities) [8]. Sometimes they don’t show the true asymmetric SV behaviour. Magnetostriiction in Co layers is well understood, being $-6 \times 10^{-5}$ for pure element [9] (constriction in magnetic field). In alloys it is mostly positive (elongation).

2. Experimental

Si (100) wafers (0.45 µm) with native oxide were used as substrates. Ten different SV structures were e-beam evaporated at RT in UHV ($10^{-7}$ Pa). (For evaporation the residual stress influencing the behaviour of SV structure should be lower as for sputtering.) The growth rates measured by quartz
monitor were 0.1 nm/s [10]. The FeCo/Cu/Co, Co/Au/Co and Co/Cu/Co core structures were deposited onto adhesion/buffer underlayer and they were covered by a top layer to prevent oxidation. In this paper results for some representative samples summarized in Table 1 will be shown.

Table 1. Studied pseudo SV structures

| #  | Underlayer [nm] | Core structure [nm] | Top layer [nm] | GMR [%] |
|----|----------------|---------------------|----------------|---------|
| 1  | Cr(3)          | Fe(3)Co(0.5)/Cu(3)/Co(5) | Cu(2)/Cr(2)    | 5.2     |
| 2  | Cr(5)/Au(2.5)  | Co(5)/Au(2.2)/Co(2)  | Au(1)          | 5.6     |
| 3  | Cr(5)/Cu(5)    | Co(2)/Cu(2.2)/Co(5)  |                | 3.3     |
| 3s | Cr(6.45)Cu(7.4)| Co(2)/Cu(1.9)/Co(5.1)|              | 3.3     |

The samples were analysed by specular X-ray reflectivity (XRR) and X-ray diffraction (XRD). The influence of magnetostriction on GMR was studied in bending configuration employing the complementarity of direct and inverse magnetostriction phenomena. Si strips 15 x 3 mm² were seated on two supports l = 12 mm apart. Force $F$ was exerted by the mass of the blocks of 50, 100 - 350 g. The stress in SV is tensile or compressive for the stack on bottom or top of the strip, respectively. Resistance was measured by four-point probe along the distance of 6 mm at RT, current and field in the plane of layered structure being mutually perpendicular. The bowing depth $y$ was 40 µm/50 g increasing linearly with the mass. Using formula $y = F.l^3/48.E.J$, where $E = 1.3 \times 10^4$ N/mm² is the Young's modulus of Si(100) and $J$ is the moment of inertia of Si strip cross section vs. neutral axis (0.03 mm⁴ in our case), $y = 45$ µm. The maximum strain in our strips is 400x10⁻⁶. This value is comparable with the strain in standard GMR strain sensors (around 0.1 % [4]).

3. Results and discussion

XRD revealed a partial crystallinity of the samples. By simulation of XRR spectra the thickness data were obtained which show small differences with those measured in situ (table 1). In the GMR structures an oscillatory exchange coupling between ferromagnetic layers vs. non-magnetic spacer thickness is known. At large negative maxima of coupling both GMR and response of SV to external magnetic field are high [11]. In Co/Au/Co structure the maxima of GMR were reported for spacer thickness 1.35 nm, 2.4 - 2.5 nm and 3.9 nm [12]. For Co/Cu/Co structure the negative maxima are at 2.1 and 3 nm [11]. The design of our structures respects these facts. Further, the change of the spacer thickness due to the bending of SV will not shift the GMR considerably on the oscillatory GMR vs. spacer thickness curve. Assuming that the period of oscillations is about 1 nm, the change of spacer thickness of 0.25 nm would shift GMR to the point of inflection of the oscillatory dependence and this could influence the output considerably (cf. [12]). However, at the bowing depth of 40 µm the elongation/constriction of our SV structures is only ± 6 µm and corresponding change of the whole SV thickness is ± 0.01 nm, which can be omitted. The same conclusion might be done in respect of the change of roughness which could also influence the GMR signal [13]. Thus, our measurements are not expected to be influences by the above discussed phenomena.

The results of our resistance vs. magnetic field measurement are as follows. In figure 1 minor loops of the sample # 1 normalized to the resistance at zero field are shown. Full antiparallel alignment is reached in the course of cycling. The results of strained sample # 1 are shown in figure 2. The highest change of the relative resistance vs. bending in the strain interval ± 300x10⁻⁶ is 1 - 2 %. Results for other samples are similar. Virgin characteristics are displayed as well. Strain dependences of the coercivity field $H_c$ and field in the point of inflection $H_{ip}$ of $R(H)/R(0)$ characteristics are shown in figure 3a. $H_c$ and $H_{ip}$ correspond to the position of the first and the second derivatives of characteristics being zero, respectively.
Figure 1. Minor resistance vs. applied field loops of sample #1 (Table 1). Dashed line – virgin characteristic, \(R(0)\) – zero field value.

Figure 2. Resistance vs. applied field characteristics of sample #1. The dashed and full lines correspond to strain of \(300 \times 10^{-6}\) and \(-300 \times 10^{-6}\), respectively. For positive strain \(H_c\) moves to higher magnetic field.

In figure 3 \(H_c\) and \(H_{ip}\) of samples #1, 2, and 3 are compared. The dependences of \(H_c\) and \(H_{ip}\) vs. strain differ, showing increase (#1), decrease (#2) or mixed behaviour (#3). Remarkable is the difference between samples #1 and #2, which could be explained by assuming that in sample #1 we have positive magnetostriction due to the intermixing of 0.5 nm thick Co layer with its Fe underlayer. This seems reasonable because 0.5 nm thick Co is discontinuous [14]. Fe-Co belongs to materials with positive magnetostriction, for Fe\(_{50}\)Co\(_{50}\) it saturates at \(10 \times 10^{-5}\) [5]. For positive magnetostriction tensile stress leads to preferred orientation of magnetization parallel to stress direction along strip. In our perpendicular configuration this results in the decrease of the slope of \(R(H)/R(0)\) characteristics [4], which means that the position of the point of inflection moves to higher fields. For increasing compressive stress we may expect decrease of \(H_{ip}\). In figures 3b and 3c for samples with negative magnetostriction of Co layers opposite trend appears. \(H_c\) follows \(H_{ip}\) behaviour, however, here also superimposed effect of stress breaking away of domain walls from their pinning sites with tending to anhysteretic state may play certain role [6] (figure 3c).
Figure 3. Coercivity field $H_c$ and field in the point of inflection $H_{ip}$ vs. strain. Samples # 1 (a), # 2 (b) and # 3 (c).

4. Conclusion
The different behaviour of coercivity vs. strain was found in SV structures with FeCo/Cu/Co, Co/Au/Co and Co/Cu/Co core structures. They seem to be related to the positive or negative magnetostriction. The relative change of MR in the strain interval $\pm 300 \times 10^{-6}$ is 1-2 %. Therefore, it does not influence the basic role of SV as sensor of magnetic field.

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