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$Ni_{80}Fe_{20}$/Au/Co/Au multilayers as magnetic field sensors

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Sputter-deposited $(Ni_{80}Fe_{20}/Au/Co/Au)_N$ multilayers characterized by alternating easy-plane (Permalloy) and perpendicular (cobalt) anisotropy were investigated. Such films can be used as giant magnetoresistance (GMR) sensors with linear $R(H)$ dependences in a broad range of magnetic fields. The influence of the thicknesses of the NiFe, Au and Co layers, and of the repetition number N on the GMR effect is discussed. We have optimised the multilayer parameters for application purposes.

Key words: *magnetic multilayers; alternating anisotropy; GMR sensors*

1. Introduction

Magnetic field sensors based on the giant magnetoresistance effect (GMR) are widely used in computer hard drives as reading heads. This application requires large changes of electrical resistance $\Delta R/R$ with small changes of the magnetic field H. Magnetic field measurements in industrial applications, on the other hand, often require sensors capable of measuring fields of up to several kOe. Magnetoresistive sensors used for such applications should exhibit linear $R(H)$ characteristics in a broad field range as well as high values of $\Delta R/R$. It has been previously shown [1, 2] that these requirements are fulfilled in layered structures of the $F_{\|}/S/F_{\perp}$ type, where $F_{\|}$ and $F_{\perp}$ are ferromagnetic layers with in-plane and perpendicular anisotropy, respectively. $F_{\|}$ and $F_{\perp}$ are separated by a nonmagnetic metallic spacer S. In this new kind of GMR -based spin valves (SV), the external magnetic field H perpendicular to the layer rotates the magnetization of the $F_{\|}$ layer and leaves the magnetization of the $F_{\perp}$ layer unchanged. If we neglect anisotropic magnetoresistance (AMR), the $R(H)$ dependence can be expressed as $R(\varphi) = R_P + (R_{AP} - R_P)(1 - \cos\varphi)/2$, where R_P and R_{AP} are the electrical resistances of the system with parallel and antiparallel magnetization configurations, respectively, and φ is the angle between the magnetizations of the ferromagnetic

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layers. For $F_{\|}/S/F_{\perp}$ structures with no coupling between ferromagnetic layers, changes in $\cos\varphi(H)$ are related only to the rotation of magnetization in $F_{\|}$ layers and can be described by: $\cos(H_{\perp}) \propto H_{\perp}$ for $|H| < H_S$. This assures a linear $R(H_{\perp})$ dependence.

Spin valves reported by Mancoff [1] used a magnetically hard Pt/Co/Pt/Pd multilayer (H_C = 5 kOe) as $F_{\perp}$. As a result, the magnetoresistance $R(H_{\perp})$ was an odd function and linear for $H_{\perp}$ in the ±5 kOe range. These valves, however, exhibit a small change in resistance of $\Delta R/R$ = 1.5% and a hysteresis of $R(H_{\perp})$ for $H_{\perp} > H_C$.

We propose multilayer sensors with the $(Ni_{80}Fe_{20}/Au/Co/Au)_N$ structure, where N is the number of repetitions, $F_{\perp}$ = Co (Co layers with thickness $t_{Co} < 1.2$ nm sandwiched between Au have perpendicular anisotropy), and $F_{\|} = Ni_{80}Fe_{20}$ (Permalloy). Such structures display high changes of resistance ($\Delta R/R$ = 9% at room temperature) and linear, non-hysteretic $R(H)$ characteristics even in H for the $H_S^{Co} < |H_{\perp}| < H_S^{NiFe}$ field range. H_S^{Co} and H_S^{NiFe} are the saturation fields (in perpendicular configurations) of the Co and NiFe layers respectively. It is worth noting that it is possible to obtain an odd dependence for $R(H)$ by applying a bias field [3].

In this paper, we discuss the influence of the thicknesses of constituent layers of the NiFe/Au/Co/Au multilayer sensor on its properties, important from the application point of view.

2. Experimental

$(Ni_{80}Fe_{20}/Au/Co/Au)_N$ multilayers (MLs) were deposited on Si(100) wafers using UHV magnetron sputtering [2, 4]. The periodic structure of MLs was controlled using LAXRD. Magnetoresistance (four-point measurements with current in the plane configuration) and magnetization reversal (vibrating sample magnetometer – VSM) were studied at room temperature for a magnetic field applied perpendicular to the sample plane ($|H_{\perp}| \leq 2$ T) (from this point we will refer to $H_{\perp}$ simply as H). The $\Delta R/R(H)$ dependence was calculated using the formula

$$\frac{\Delta R}{R}(H) = \frac{R(H) - R(H = 2\ \mathrm{T})}{R(H = 2\ \mathrm{T})} \times 100\%$$

where $\Delta R/R$ denotes the maximum value determined from the $\Delta R/R(H)$ dependence.

3. Results and discussion

Figure 1 shows the magnetization reversal $M(H)$ and the magnetoresistance $R(H)$ curves typical of the $(Ni_{80}Fe_{20}/Au/Co/Au)_N$ system. There are three distinctive field ranges in the magnetization curves: (i) $|H| > H_S^{NiFe} = 0.6\ \mathrm{T} = 4\pi M_S^{NiFe}$, corresponding to a parallel magnetization configuration of Co and $Ni_{80}Fe_{20}$ layers, (ii) H_N^{Co}

(H_S^{Co}) < |*H*| < H_S^{NiFe} (H_N^{Co} and H_S^{Co} are the domain nucleation and annihilation fields of Co, respectively), which is related to the coherent rotation of magnetization in $Ni_{80}Fe_{20}$ layers, and (iii) |*H*| < H_N^{Co} (H_S^{Co}), related mainly to magnetization reversal in Co layers. Magnetic structure in the third range is dominated by strong ferromagnetic dipolar magnetostatic coupling (caused by a dense stripe domain structure) between NiFe and Co layers [5]. From the application point of view, the second field range, in which for H_S^{Co} < |*H*| < H_S^{NiFe} a linear and non-hysteretic *R*(*H*) dependence can be obtained, is the most interesting.

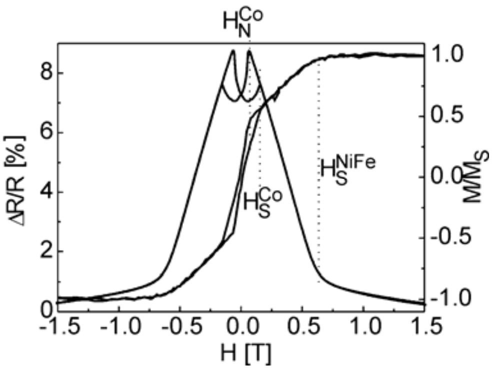


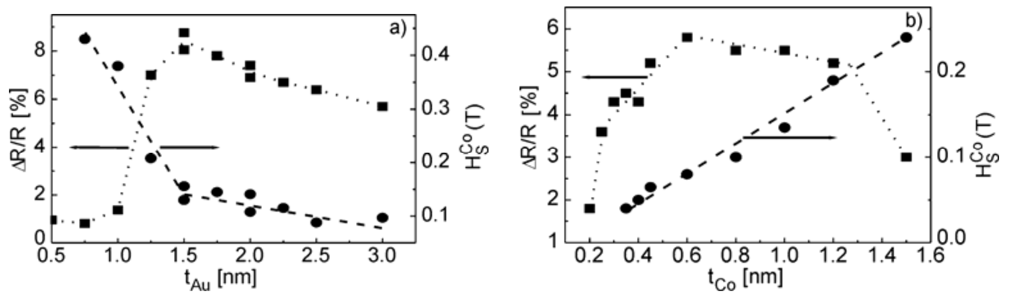
Fig. 1. Magnetoresistance and hysteresis loop of the (NiFe 2 nm/Au 1.5 nm/Co 0.6 nm/Au 1.5 nm)$_{15}$ multilayer, measured with the magnetic field applied perpendicular to the sample surface. The characteristic magnetic fields H_N^{Co}, H_S^{Co}, and H_S^{NiFe} denote the nucleation, annihilation (saturation) of stripe domains of Co layers, and saturation of Permalloy layers, respectively

The magnetization reversal and magnetoresistance of our structures are influenced by coupling between ferromagnetic layers and their magnetic properties (mainly anisotropy). This behaviour is similar to other SVs [6]. In order to determine the influence of Au, Co, and NiFe layer thickness on the magnetoresistive properties of $(Ni_{80}Fe_{20}/Au/Co/Au)_N$ MLs, we investigated three series of samples:

- $(Ni_{80}Fe_{20}$ 2 nm/Au t_{Au}/Co 0.6 nm/Au $t_{Au})_{15}$ (0.5 ≤ t_{Au} ≤ 3 nm),
- $(Ni_{80}Fe_{20}$ 2 nm/Au 3 nm/Co t_{Co}/Au 3 nm$)_{15}$ (0.2 ≤ t_{Co} ≤ 1.5 nm),
- $(Ni_{80}Fe_{20}$ t_{NiFe}/Au 2 nm/Co 0.6 nm/Au 2 nm$)_{15}$ (1 ≤ t_{NiFe} ≤ 4 nm).

The dependence of Δ*R*/*R* on t_{Au} (Fig. 2a) is related to changes in effective coupling. The $H_S^{Co}(t_{Au})$ dependence, with a kink at $t_{Au} \approx 1.5$ nm, suggests that two different mechanisms are responsible for the observed changes in interlayer coupling. The first one is the relatively weak magnetostatic coupling (Néel's coupling), important in the whole range of t_{Au}. The second one, dominating for $t_{Au} < 1.5$ nm, is much stronger and probably originates from pinholes. The role of relatively weak ($t_{Au} > 1.5$ nm) RKKY -like coupling can be neglected. As a consequence of such changes in coupling, a strong degradation of GMR for $t_{Au} < 1.5$ nm is observed. The slow decrease of the magnetoresistance Δ*R*/*R*(t_{Au}) for $t_{Au} > 1.5$ nm can be attributed to the shunting effect [7].

The Δ*R*/R(t_{Co}) dependence (Fig. 2b) exhibits a maximum at $t_{Co} = 0.6$ nm, which corresponds to the transition from a discontinuous to continuous Co layer. In the $0.6 < t_{Co} < 1.2$ nm range, magnetoresistance decreases slowly. This change can be attributed to the diminishing influence of interface spin scattering compared to that within the Co layer [8]. The sudden drop in magnetoresistance at $t_{Co} > 1.2$ nm is related to the transition from perpendicular to in-plane anisotropy in Co layers. The monotonic increase of H_S^{Co} with t_{Co} is typical of ferromagnetic layers with stripe domains [9].



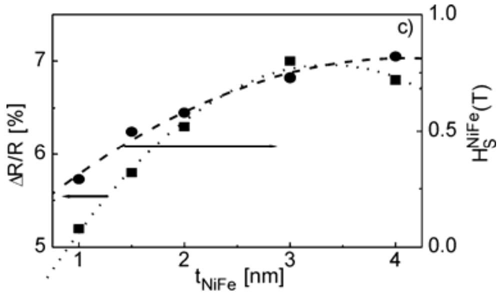


Fig. 2. Changes in magnetoresistance as functions of t_{Au}, t_{Co}, and t_{NiFe} determined for (NiFe 2 nm/Au t_{Au}/Co 0.6 nm/Au t_{Au})$_{15}$ (a), (NiFe 2 nm/Au 3 nm/Co t_{Co}/Au 1.5 nm)$_{15}$ (b), and (NiFe t_{NiFe}/Au 2 nm/Co 0.6 nm/Au 2 nm)$_{15}$ (c) MLs, respectively. The saturation fields of Co layers (H_S^{Co}) and Permalloy (H_S^{NiFe}) are also plotted in panels a, b and c, respectively

Magnetoresistance as a function of Permalloy layer thickness (Fig. 2c) exhibits a maximum at much higher values ($t_{NiFe} \approx 3$ nm) than that observed for Co. This can be explained by the predominant contribution of volume spin scattering in $Ni_{80}Fe_{20}$ to the magnetoresistance effect [8].

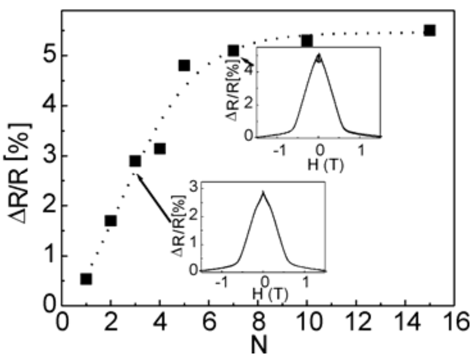


Fig. 3. The magnetoresistance of (NiFe 2 nm/Au 3 nm/Co 0.8 nm/Au 3 nm)$_N$ MLs vs. repetition number N. The insets show the field dependences of resistance for MLs with $N = 3$ and $N = 7$

The increase of H_S^{NiFe} with t_{NiFe} is similar to that observed for NiFe/Cu multilayers [10] and in the first approximation can be interpreted as a result of a magnetically inactive NiFe/Au interface layer. The strong H_S^{NiFe} (t_{NiFe}) dependence observed for small values of t_{NiFe} offers a simple way of tailoring the saturation fields of $\Delta R/R(H)$ in our structures. Larger values of t_{NiFe}, however, lead to an increase of the anisotropic magnetoresistance effect (AMR) and deteriorates the linearity of $R(H)$.

Our investigation proved that $(NiFe/Au/Co/Au)_{15}$ MLs with $1.5 \le t_{Au} \le 0.8$ nm, $0.6 \le t_{Co} \le 0.8$ nm, and $2 \le t_{NiFe} \le 3$ nm can be used as sensors with linear $R(H)$ characteristics in a broad field range and for relatively large $\Delta R/R$.

The number of repetitions, N, is the next parameter that greatly influences the magnetoresistance of layered structures (Fig. 3). The increase of $\Delta R/R$ with N is mainly the result of the diminishing role of electron scattering at the sample surfaces. We believe that low magnetoresistance for low N is most likely caused by imperfections in the first period and subsequent lack of perpendicular anisotropy in Co. This interpretation is corroborated by the low $\Delta R/R$ value (0.5%) observed for $N = 1$ and the distinct kink in $\Delta R/R(H)$ for $N = 3$. For $N \ge 7$, the dependence of $\Delta R/R(H)$ saturates and the influence of the first layer becomes negligible.

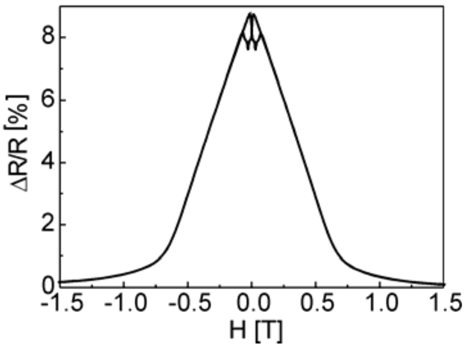


Fig. 4. The magnetoresistance of (Co 3.2 nm/Au 2 nm/Co 0.8 nm/Au 2 nm)$_3$ MLs deposited on a Si(100) substrate with a (Au 2 nm/Si 1 nm)$_3$ buffer layer

In order to increase GMR, the NiFe layers were replaced by 3.2 nm thick Co layer. Cobalt displays a higher spin polarization than NiFe, and for that t_{Co} the effective anisotropy is in-plane and the saturation field H_S^{Co} (3.2 nm) ≈ 0.7 T. In (Co 3.2 nm/Au 2 nm/Co 0.8 nm/Au 2 nm)$_3$ structures deposited on high-resistance (Au 2 nm/Si 1 nm)$_3$ buffer layers, the $\Delta R/R(H)$ dependences (Fig. 4) are similar to those observed for (NiFe/Au/Co/Au) MLs with N > 7 (Fig. 1). The low total thickness of Mls ($N = 3$) results in high $R/\square$ (sheet resistance), which is very desirable for sensor applications.

4. Conclusions

We have studied the magnetoresistance of $(Ni_{80}Fe_{20}/Au/Co/Au)_N$ multilayers as functions of the repetition number and $Ni_{80}Fe_{20}$, Au, and Co thickness. We have identified a set of parameters for which the $R(H)$ dependence is linear and non-hysteretic in the range $0.2 \le |H| \le 0.6$ T and displays $\Delta R/R \approx 6\%$ at RT. For structures in which $Ni_{80}Fe_{20}$ layers were replaced by 3.2 nm thick Co, a broader range of linearity

(0.1 ≤ |*H*| ≤ 0.6 T) and higher GMR values ($\Delta R/R \approx 6.5\%$) were observed. The presented structures are promising candidates for magnetic field sensors.

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