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MATERIALS FOR SPIN-VALVES[1]

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Spin valve structures of Co/Cu/Co, Co/Au/Co, and Fe/Co/Cu/Co types were fabricated by electron beam deposition. Cr or Cr/M (M=Ag, Au, Cu) layers were used as buffer layers. Layer thicknesses and interface roughnesses were determined by the X-ray reflectivity while internal structure of the layers was analyzed by the X-ray diffraction. Magnetoresistance (MR) data indicate the effect of both buffer and magnetic layer thicknesses on the magnetic field dependence of the MR. We investigated the influence of Cu, Ag and Au layers on the value of magnetic field necessary to reverse the polarization of magnetic layers of different thicknesses. The largest value of such a magnetic field was obtained for 5nm Cr/2.5nm Au/5nm Co/2.2nm Au/2nm Co/1Au multilayer.

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1 Introduction

The Giant Magneto-Resistance (GMR) effect was discovered nearly 20 years ago [1,2] and nowadays GMR-based products are already available commercially. The GMR ratio is usually defined as (R(0)-R(B))/R_{sat} where R(0) and R_{sat} correspond to the resistance in the zero and saturated magnetic fields, respectively. The GMR occurs in layered structures formed by magnetic layers separated by non-magnetic spacers. The electrical resistance varies according to the angle between the magnetic moments in the two adjacent magnetic layers. For parallel moments, the resistance takes up a minimum value. We may easily realize this arrangement by applying a field large enough to saturate all the magnetic layers. On the other hand, the antiparallel moments give a high resistance state. The earliest GMR structures relied on very thin spacer layers where the indirect exchange coupling provides antiferromagnetic alignment of the layers at zero field. An alternative arrangement is the use of a spin-valve structure which was invented shortly after the GMR discovery [3]. Here, the two magnetic layers are separated by a non magnetic spacer where the magnetic moment of one layer is pinned so that it cannot be rotated in moderate fields while it is free to rotate in the other layer. Recently, spin valve structures with magnetic layers

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of the same material but of different thicknesses resulting in different coercitivities were also reported [4]. The spin valve effect enables us to switch easily between the parallel and antiparallel configurations, its sensitivity being still higher than that of GMR multilayers. Moreover, there is a possibility to distinguish between positive and negative fields.

The purpose of this paper is to describe our development of a spin-valve sensor using the ultrahigh vacuum (UHV) electron beam evaporation to deposit the metal layers. It is known that the best GMR multilayers with the antiferromagnetic coupling are prepared by sputtering (magnetron or ion beam) technique. Electron beam deposited multilayers or MBE grown structures often exhibit a smaller GMR signal [5,6].

2 Experimental

Silicon wafer substrates were used to grow our spin-valve films. The native oxide coating of the wafers provides a very smooth surface. The samples were deposited at room temperature by electron beam evaporation in an UHV deposition system with the base pressure of 10^{-7} Pa. The growth deposition rates were typically 0.1 nm/s. The magnetoresistance measurements were carried out in a four-probe configuration with in-line gold-plated contacts. The measurements were performed at room temperature with the magnetic field applied in the sample plane and perpendicular to the current in this plane (in-plane current geometry). To study magnetic hysteresis effect, all measurements were made in a cyclic field of 0T $\rightarrow$ B_{max} $\rightarrow$ 0T $\rightarrow$ -B_{max} $\rightarrow$ 0T $\rightarrow$ B_{max} $\rightarrow$ 0T.

The multilayer stack of the samples was analysed by specular X-ray reflectivity (XRR) using $CuK_{\alpha 1}$ radiation which provided layer thicknesses and effective roughness of the interfaces. The X-ray diffraction at the same wavelength revealed a partial crystallinity of the samples.

3 Results and Discussion

Three basic spin valve structures were prepared and studied, namely Co/Cu/Co, Co/Au/Co, and Fe/Co/Cu/Co. For all systems, magnetic layers of different coercitivities (different Co thicknesses or a combination of Fe and Co layers) were used. The parameters of the layered structures starting from the substrate are summarized in Table 1. Cr layer or Cr/M (M=Cu, Ag, Au) bilayers were used as buffer layers. Only the materials immiscible with Co could be used to prevent the mixing at the interface with Co layer. A top Au layer was used to prevent the oxidation of the upper Co layer. A typical magnetic field dependence of the GMR is shown in Fig. 1 for the 5nm Cr/1.5nm Au/5nm Co/2.2nm Au/2nm Co/1nm Au sample. Derivative of the GMR curve, d(GMR)/dB, was used for the evaluation of the spin valve structure (Fig. 2). The B_h value is defined as the half of the distance between the external peaks, $(-B_{h-}+B_{h+})/2$, corresponding to the magnetic induction with the steepest drop of the resistance. The B_l value corresponds to the half value of the magnetic induction between the internal peaks of the GMR derivative. We believe that this is a better characteristics than the half peak width as the steepest changes in the resistance follow the steepest changes in the magnetization curves which correspond to the layer coercitivities.

The Co/Cu/Co and Fe/Co/Cu/Co systems (samples 1-4) show behaviour similar to that reported for sputtered samples [4,7]. A lower GMR was found for Co/Cu/Co sample when thicker

Tab. 1. Composition of the samples. The numbers at chemical symbols represent the layer thicknesses in nm, GMR=((R_{max}-R_{min})/R_{min})×100, B_h and B_l are defined in the text.

Sample no.	Composition	GMR [%]	B_h [mT]	B_l [mT]
1	3Cr/3Fe/3Cu/5Co/2Cu/2Cr	2.33	13	7.75
2	3Cr/3Fe/0.5Co/3Cu/5Co/2Cu/2Cr	5.17	15.6	8.6
3	5Cr/5Cu/5Co/2.2Cu/2Co	4.22	13.2	5.4
4	5Cr/5Cu/2Co/2.2Cu/5Co	3.31	11.25	5.4
5	5Cr/5Cu/5Co/2.2Au/2Co/1Au	2.85	8.25	3.8
6	5Cr/5Ag/5Co/2.2Au/2Co/1Au	1.95	13.35	8.25
7	5Cr/5Au/5Co/2.2Au/2Co/1Au	3.81	25.7	18.65
8	5Cr/2.5Au/5Co/2.2Au/2Co/1Au	5.64	27.65	18.15
9	5Cr/1.5Au/5Co/2.2Au/2Co/1Au	5.49	22.25	15.0
10	2Cr/1.5Au/4Co/2.2Au/2Co/1Au	4.26	14.0	5.4
11	2Cr/1.5Au/2Co/2.2Au/2Co/1Au	2.35	5.75	1.5

Co layer was deposited on the top (sample 4). For Fe/Cu/Co system, addition of a thin Co layer between Fe and Cu increased the GMR considerably (sample 2). This sample also shows slightly higher values of B_h and B_l.

For the Co/Au/Co combination (sample 5), a lower GMR value in comparison with that of Co/Cu/Co (sample 3) is found. The B_h and B_l values are also lower for the sample 5 with the Au spacer. Both the GMR and B_h, B_l values are affected by the choice of the buffer layer. Among different combinations of Cr/M buffer bilayer (M=Cu, Ag, Au), Au proved to be the best choice (sample 7).

From Table 1 it follows that the use of Au layers leads to much higher values of B_h and B_l, the switching magnetic induction. The maximum GMR is quite high taking into account that there is a highly conductive shunt created by the buffer layer. It is possible to reach a higher GMR by making these layers thinner (see the samples 7-9). It should be noted that for the Au buffer layer 1.5 nm thick, an intermixing between the Cr underlayer and Co overlayer may appear, most probably due to the island structure of the Au layer. This effect was observed for some samples

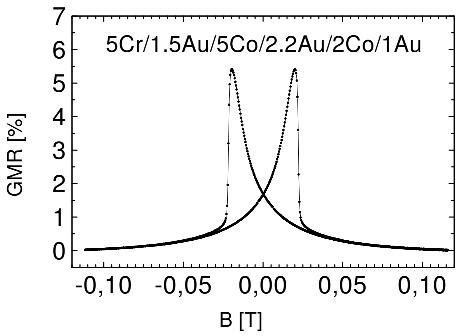

Fig. 1. Magnetoresistance of spin-valve 5nmCr/1.5nmAu/5nmCo/2.2nmAu/2nmCo/1nmAu.

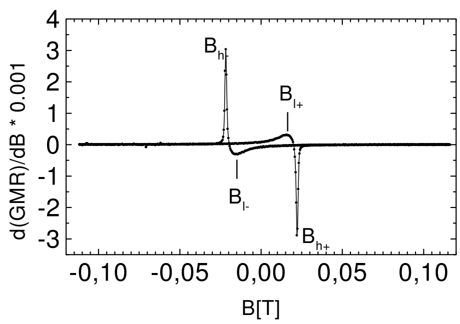

Fig. 2. Derivative of the magnetoresistance curve from Fig. 1

when the mixing and a possible Co-Cr mixture formation deteriorated the parameters of the spin valve. Therefore, the thickness of the Au buffer layer of 2.5 nm is considered as the most suitable in our samples.

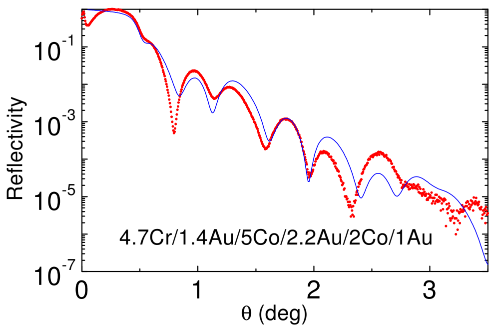

Fig. 3. XRR measurement of the sample 5nmCr/1.5nmAu/5nmCo/2.2nmAu/2nmCo/1nmAu (dots) and simulation (line) based on the Fresnel optical approach which provided the real layer thicknesses indicated in the figure.

An expected decrease of the GMR, B_h, and B_l values with decreasing pinned Co layer thickness is evident from a comparison of the samples 9,10,11 with equal free Co layer thicknesses. However, the effect of a possible intermixing between the Cr and Co layers across the island-like separating Au layer, which is more pronounced for thinner Co layers, cannot be excluded either.

The XRR results show well defined interference fringes revealing a good quality of the interfaces and confirming that the designed layer thicknesses agree with the real ones within 20 percent. For the sample 9, the XRR measurement together with its simulation are shown in Fig. 3. The X-ray diffraction revealed a partial crystallinity of the samples.

4 Conclusions

We prepared a variety of spin-valve stacks consisting of magnetic Co or Fe/Co and non-magnetic Cu, Ag or Au layers deposited by electron beam evaporation. Their GMR values are comparable to those deposited by magnetron or ion beam sputtering. The GMR behaviour exhibits an abrupt low field switching for the magnetically soft layer and a gradual high-field switching for the hard layer. The layer arrangement and choice of the materials influence the performance considerably. The best results were obtained for the 5Cr/2.5Au/5Co/2.2Au/2Co/1Au, 5Cr/5Cu/5Co/2.2Cu/2Co and 3Cr/3Fe/0.5Co/3Cu/5Co/2Cu/2Cr stacks. The Au buffer layer in combination with Cr was found to provide the highest switching magnetic fields.

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