J. Nano- Electron. Phys.
3 (2011) No4, P. 81-87

PACS numbers: 75.30.Ds, 75.47.De, 75.30.Gw

MAGNETORESISTIVE PROPERTIES OF SPIN-VALVE STRUCTURES BASED ON Co AND Cu OR Au

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The construction of module for the automated measurement of the magnetoresistance (MR) and coercive force (B_c) in spin-valve structures based on Co *and* Cu *or* Au *film systems was proposed. The peculiarities of dependences of MR and B_c from angle α between substrate plane and direction of the external magnetic field induction were studied. The abrupt changes of MR and B_c in the range of α = 70°-90° were observed. The dependence character of MR from α is defined by the degree of solubility of atoms of the bottom ferromagnetic layer* Co*(3 nm) or* Co*(20 nm) in layer* Cu*(6 nm), since* Co*(3 nm) atoms are dissolved almost completely, but* Co*(20 nm) ones – only partially. In this case, remagnetization of magnetic layers of* Co*(20 nm) and solid solution (s.s.) [*Cu, Co*(3 nm)] as well as* Co*(3 nm) and [*Co*(20 nm-x)] + s.s.[*Cu, Co*(x)] is realized in different ways. This fact causes an increase or decrease of MR.*

Keywords: *SPIN-VALVE, MR, INDUCTION OF MAGNETIC FIELD, COERCITIVITY.*

(Received 07 September 2011, in final form 04 October 2011, online 30 December 2011)

1. INTRODUCTION

Phenomenon of the giant magnetoresistance (GMR) is studied in detail on the example of different film systems. Scientists pay much attention to the investigation of the GMR in spin-valve structures [1-3]. The value of the GMR depends on many factors, in particular, measurement geometry. The value of the angle α between the external magnetic field direction and the current flow plane has a substantial influence on the magnetoresistive properties of film systems. One can mark out two main geometries of the applied magnetic field: FIP (lines of magnetic induction are parallel to the plane of film system) and FPP (lines of magnetic induction are perpendicular to the sample), and two geometries of current transmission through the film system: CIP (direction of current transmission is parallel to the sample plane) and CPP (current direction is perpendicular to the film system plane).

The aim of the given paper consisted in the development of the module of automated complex for measurement of the MR and coercitivity depending on the angle α.

2. EXPERIMENTAL TECHNIQUE

During the experimental investigation of the magnetoresistive properties of spin-valve structures, the following multilayer film systems versus the direction of the external magnetic field action were studied:

Au(1 nm)/Co(3 nm)/Au(6 nm)/Co(20 nm)/SiO2/Si (spin-valve No1);
Au(1 nm)/Co(3 nm)/Cu(6 nm)/Co(20 nm)/SiO2/Si (spin-valve No2);
Au(1 nm)/Co(20 nm)/Au(6 nm)/Co(3 nm)/SiO2/Si (spin-valve No3);
Au(1 nm)/Co(20 nm)/Cu(6 nm)/Co(3 nm)/SiO2/Si (spin-valve No4).
These samples represent spin-valve structures obtained by the electron beam deposition method in vacuum at the residual gas pressure 10^{-7} Pa on monocrystalline silicon substrates with natural layer of silicon dioxide. Thickness control was carried out by the quartz resonator method during condensation. Peculiarity of the systems consists in the difference of the material of non-magnetic sublayer (copper or gold) and different thickness of the upper and bottom magnetic Co layer (3 or 20 nm).

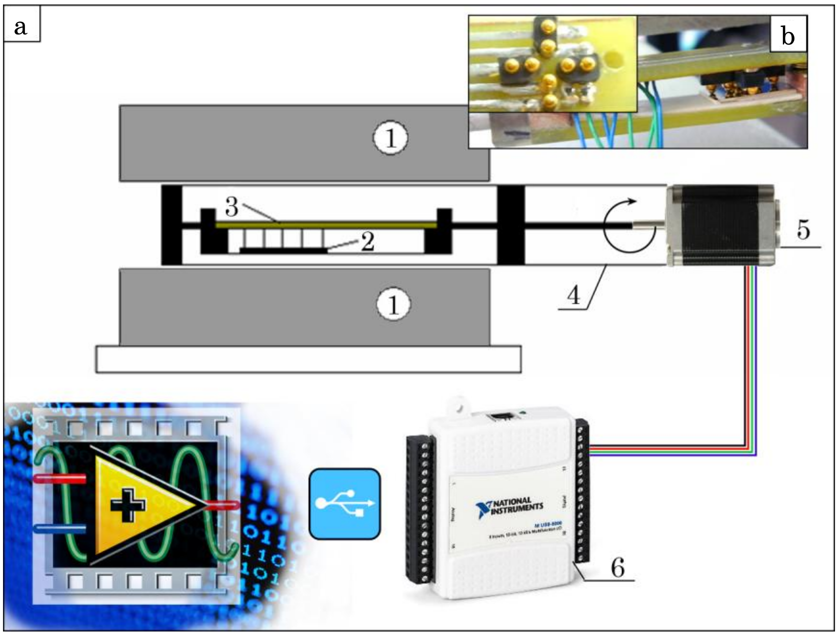

Fig. 1 *– Schematic representation of the developed module with the sample turn mechanism (a) and external view of the contacts (b): 1 – limb of electromagnet; 2 – sample; 3 – contact holder; 4 – cantilever of the sample turn mechanism; 5 – stepper motor; 6 – module for the data acquisition NI USB 6008*

In the given work we have studied the magnetoresistive properties of spin-valve systems based on Co and Cu or Au during the transition from the perpendicular to the transverse measurement geometry. Geometry change was realized by the turn of the sample in space inside the limb of electromagnet. To establish the necessary geometry, the module for automated complex of the MR change measurement was developed. The complex consists of electromagnet, unipolar power unit of electromagnet Philips PM 2811, multimeter for the resistance measurement Keithley 2000 Digital, 12-bit ADC-DAC NI USB 6008, system of relays for the change of the magnetic field sign, and module of the sample turn. Structural scheme of the module of the sample turn and its control is represented in Fig. 1. The developed module is placed inside the limb of electromagnet (Fig. 1a, pos. 1) and consists of cantilever (pos. 4) on which the contact holder (pos. 3) is fastened, table for the sample placement (pos. 2), and stepper motor (pos. 5) which is operated by DAQ NI USB 6008 (pos. 6). Contacts are golden and round-shaped that minimizes the resistance of ohmic contact with the sample and makes impossible its damage during placement into the holder. Contacts are placed in such a way (Fig. 1b) that it is possible to change the geometry of current flow with respect to the applied external magnetic field without change of the spin-valve position. Measurements of the resistance were carried out by the standard 4-probe scheme in spin-valves with parallel (CIP) geometry of the current flow.

Principal feature of the developed complex is the possibility of automated measurement of the MR change in thin-film systems in different measurement geometries, including transition from the perpendicular (Fig. 2a) to the transverse (Fig. 2b); and possibility of the sample turn during measurements in the angle range of ± 180° with the minimum step of 1° is realized.

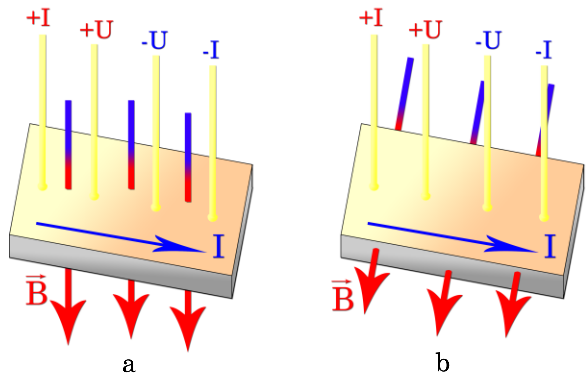

Fig. 2 – *Scheme of the perpendicular (a) and transverse (b) measurement geometries*

The considered complex is operated by software developed in the graphic programming environment LabVIEW 2010 SP1. Interface panel of the program is illustrated in Fig. 3.

Measurement results are represented in the graph (Fig. 3, pos. 1). Group of buttons (pos. 2) is used for the sample turn by the necessary angle. Button (pos. 3) allows to call the subprogram for the initial adjustment of devices Keithley 2000 Digital and DAQ-mx NI USB 6008, setting of the necessary turn angles during measurement, number of cycles, and measurement velocity. Button (pos. 4) starts the measurement process of MR. Group of indicators (pos. 5 and pos. 7) informs about the value of the magnetic field induction, state of the operation, sample turn angle, and magnetic field sign. Group of buttons (pos. 6) allows to process the measurement results.

3. RESULTS

During the experimental investigations we have obtained the dependences of the change in MR and coercitivity versus the applied external magnetic field in different geometries for spin-valve structures with CIP geometry of the current flow: No1-4.

In Fig. 4 we present the experimental dependences of the change in MR on the external magnetic field B under its action at the angles α = 0°-90°.

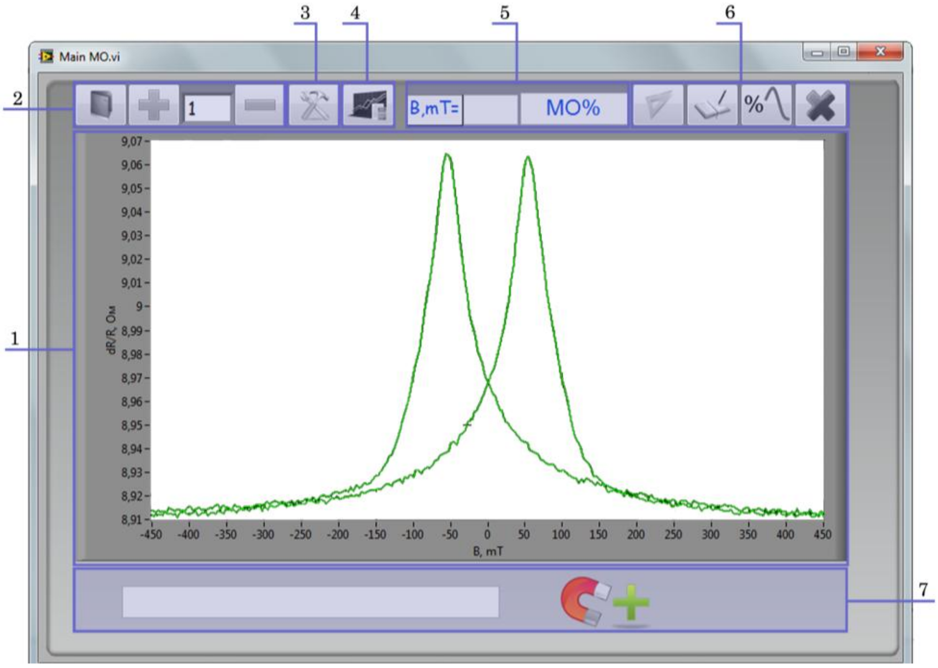

Fig. 3 *– Interface panel of the developed software: 1 – graph of the representation of the measurement results; 2 – group of buttons for the sample turn control; 3 – call of the subprogram for the measurement mode adjustment; 4 – measurement start button; 5, 7 – indicators of the state of the program work and service messages; 6 – group of buttons for the measurement result processing*

It is seen from Fig. 4 that considerable change in MR occurs if approach to the perpendicular geometry of the magnetic field application, when plane of the film system is at the angle of $\alpha = 90°$ to the direction of the external magnetic field action. In Fig. 5 we show the dependences of the change in MR on the magnetic field induction at its action in the angle range of 80°-90°.

Based on the data presented in Fig. 4 and Fig. 5, generalized results of the maximum value of MR change at the corresponding coercitivity and angle between the sample plane and the direction of lines of magnetic induction is given in Table 1.

Table 1 *– Generalized results of the maximum value of MR change for each studied spin-valve system*

System	MR, %	B_c, mT	α, degrees
Au(1)/Co(3)/Au(6)/Co(20)/SiO_2/Si	0,80	2,76	50
Au(1)/Co(3)/Cu(6)/Co(20)/SiO_2/Si	0,77	2,88	30
Au(1)/Co(20)/Au(6)/Co(3)/SiO_2/Si	1,48	3,94	20
Au(1)/Co(20)/Cu(6)/Co(3)/SiO_2/Si	2,13	68,47	90

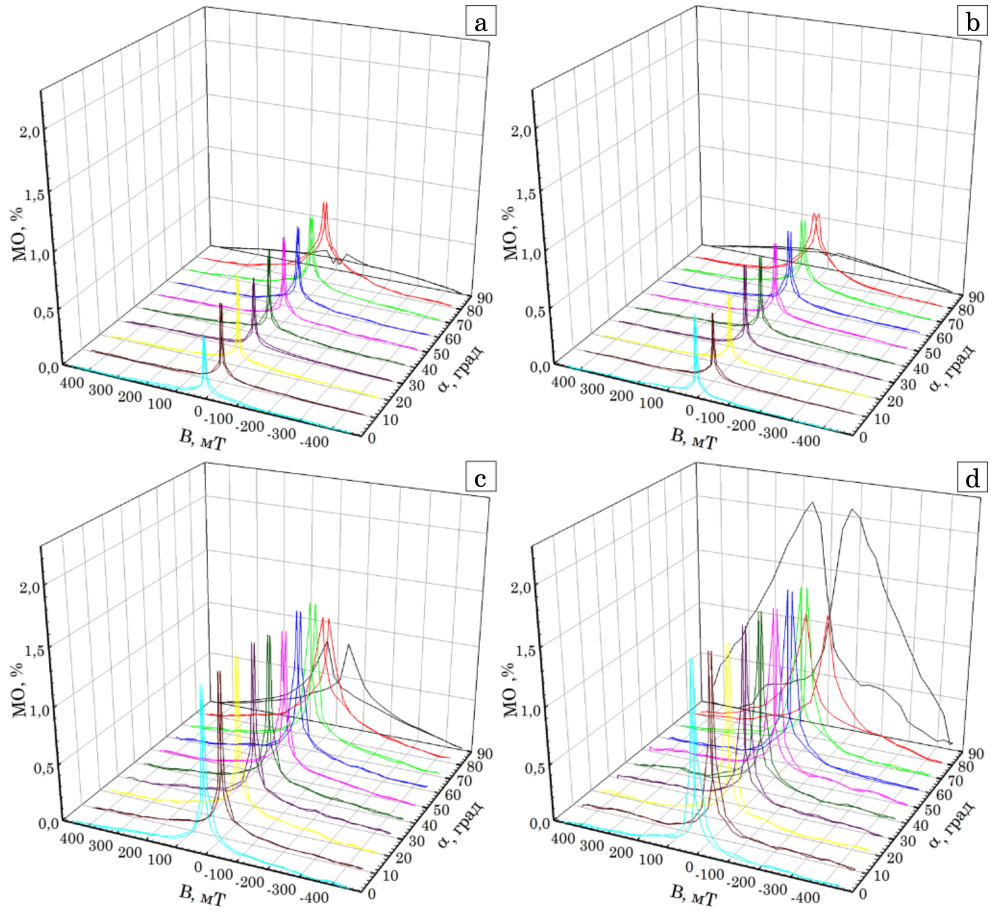

***Fig. 4** – Experimental dependences of the MR change on the magnetic field induction at the angles of* 0°-90° *for spin-valves: No1 (a), No2 (b), No3 (c), and No4 (d)*

4. DISCUSSION OF THE RESULTS

The fact that the value of the MR change almost does not depend on the angle α in the range of α = 0°-70° is the distinctive feature of the investigation results. In the range of α = 70°-90° the value of MR is sharply decreased in the case of spin-valves No1-3 or, inversely, is sharply increased in spin-valve No4. This is illustrated by the dependences of MR on the value of B at different angles of its orientation with respect to the substrate plane (Fig. 6a). In the case of the coercitivity (Fig. 6b) its value also almost does not depend on the angle α in the range of α = 0°-70°. This is connected with the presence of the easy magnetization axis in this range, which allows to magnetize and remagnetize spin-valve structures at small field. Sharp increase in the coercitivity in the range of α = 0°-90° for all four types of spin-valves can be explained by the anisotropy of Co layers in the substrate plane.

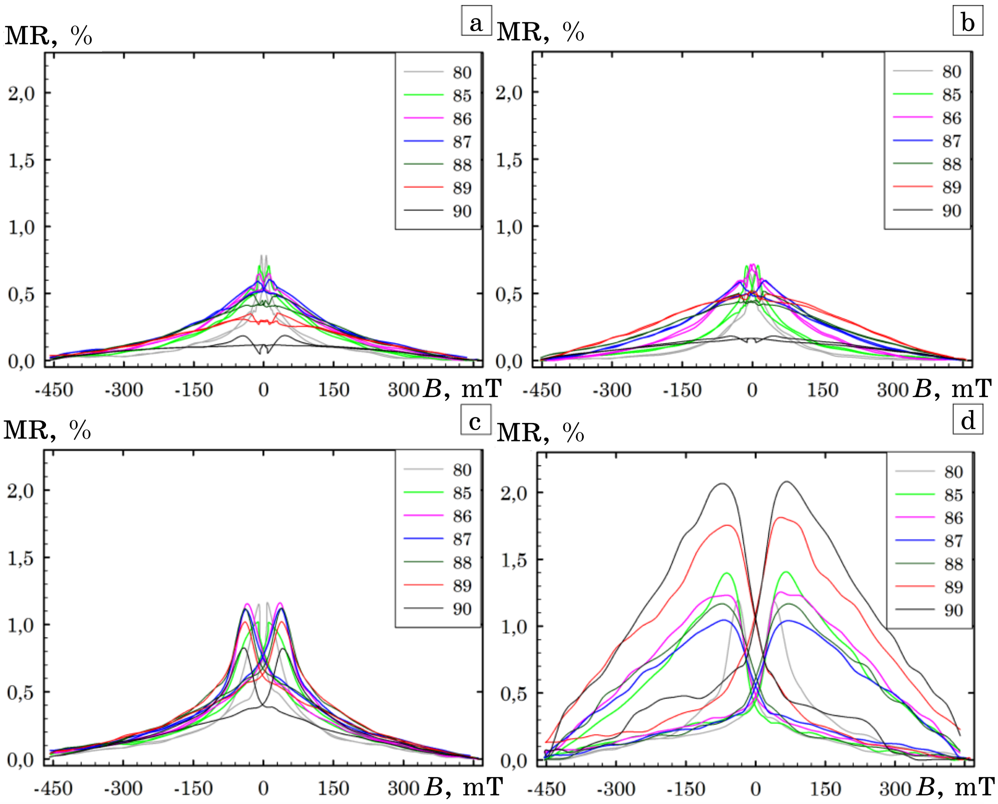

Fig. 5 – *Experimental dependences of the MR change on the magnetic field induction at the angles of* 80°-90° *for spin-valves: No1 (a), No2 (b), No3 (c), No4 (d)*

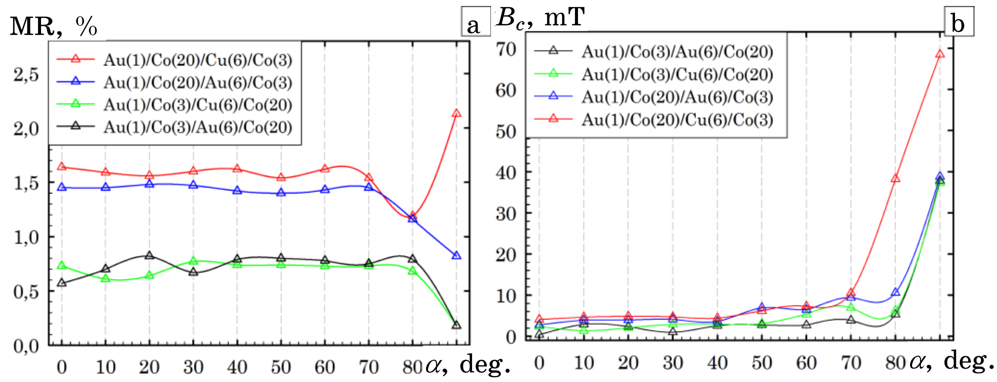

Fig. 6 – *Dependences of the change in MR (a) and coercitivity (b) on the angle of the external magnetic field action for spin-valve structur*es

For right interpretation of the obtained results, it is necessary to note that spin-valve No1 and No2 have classical structure, where bottom "fixing" ferromagnetic Co(20) layer is more hard-magnetic in comparison with the upper soft-magnetic Co(3) layer, which starts to remagnetize at smaller value of the external magnetic field induction if compare with Co(20) layer. Sharp change in the MR occurs in the induction range when Co(3) and Co(20) layers start to remagnetize that takes place, most likely, in the range of $\alpha = 70°\text{-}90°$. Permutation of these layers in spin-valves No1 and No3 does not lead to the change in the behavior of the dependences of MR and B_c on the angle α with the exception of spin-valve No4. Structure feature of this spin-valve consists in the fact that Co(3) layer borders with Cu(6) layer forming solid solution s.s. (Cu, Co) with unlimited solubility and elements of granulated state on the stage of condensation of multilayer film system as it is described by the authors of [4, 5]. Peculiarity of remagnetization of the s.s. layer leads to the "anomalous" dependence of MR on α. At the replacement of Cu(6) by Au(6), s.s. (Au, Co) is also stabilized, but with very limited solubility [4-6] that does not influence the remagnetization process of Co(3) layer. In the case of the fixing Co(20) layer, it is dissolved only partially preserving its individuality and does not lead to the considerable effect on the MR change of spin-valve structures.

5. CONCLUSIONS

We have carried out the investigations of MR and coercitivity B_c of four types of spin-valve structures based on Co and Cu or Au layers versus angle α between SiO_2/Si substrate plane and direction of the external magnetic field induction. It is established that in the range of $\alpha = 0°\text{-}70°$ change in MR and B_c almost does not depend on α, but at $\alpha = 70°\text{-}90°$ MR is decreased in the case of spin-valves No1, No2, and No3, and B_c is sharply increased for these spin-valves. Behavior of the dependences is the same for three cases of spin-valves irrespective of the thickness of the fixing Co layer (3 nm or 20 nm). Anomalous increase in MR is observed in spin-valve No4 that is explained by the formation of s.s. of Co(3) and Cu(6) layers during condensation of multilayer film system.

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