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GIANT MAGNETORESISTANCE OBSERVED IN THIN FILM NiFe/Cu/NiFe STRUCTURES

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Abstract. *In this paper, the technology for fabricating NiFe/Cu/NiFe layered structures by magnetron sputtering is presented. Two series of samples were fabricated on a glass substrate with a layered structure, where the individual layers were 30 nm NiFe, 5 nm Cu, and finally NiFe with a thickness of 30 nm. The series differed in the type of technology mask used. A constant magnetic field was applied to the substrate during the sputtering of the ferromagnetic layers. Measurements of the DC resistance of the obtained structures in the constant magnetic field of neodymium magnet packs with a constant magnetic field of about 0.5 T magnetic induction have been carried out. Comparison of the two series allows us to conclude the greater validity of using masks in the form of kapton tape. The obtained results seem to confirm the occurrence of phenomena referred to as the giant magnetoresistance effect.*

Keywords: magnetoresistance, sputtering, thin films, static magnetic field

ZJAWISKO GIGANTYCZNEGO MAGNETOOPORU OBSERWOWANE W CIENKICH STRUKTURACH NiFe/Cu/NiFe

Streszczenie. *W pracy przedstawiono technologię produkcji struktur warstwowych NiFe/Cu/NiFe metodą rozpylania magnetronowego. Wykonane zostały dwie serie próbek na szklanym podłożu o strukturze warstwowej, gdzie poszczególne warstwy stanowiły 30 nm NiFe, 5 nm Cu oraz ostatecznie NiFe o grubości 30 nm. Serie różniły się rodzajem zastosowanej maski technologicznej. Podczas napylania warstw ferromagnetycznych do podłoża przyłożone zostało stałe pole magnetyczne. Przeprowadzone zostały pomiary rezystancji stałoprądowej otrzymanych struktur w stałym polu magnetycznym okładów magnesów neodymowych o stałym polu magnetycznym o wartości indukcji magnetycznej około 0,5 T. Porównanie obu serii pozwala stwierdzić większą zasadność stosowania masek w postaci taśmy kaptonowej. Otrzymane wyniki zdają się potwierdzać występowanie zjawisk określanych jako efekt gigantycznego magnetooporu.*

Słowa kluczowe: magnetorezystancja, napylanie, cienkie warstwy, statyczne pole magnetyczne

Introduction

Sensors for physical measurements are key components of almost all electronic devices. The purpose of using them is to collect information about the environment in order to process it and put it to a specific use. Sensors for specific physical quantities can be based on completely different physical phenomena. By discovering new physical relationships and effects, new sensors can be designed and existing ones improved to increase their signal processing capabilities, e.g., by increasing their range or sensitivity. This also applies to magnetic field sensors. Currently, the best known sensors for magnetic field measurements are those based on the Hall effect. In 1856 Lord Kelvin observed resistance changes in ferromagnetic metals (iron and nickel) when an external magnetic field was applied. The group of effects, that includes the phenomenon observed by Kelvin, are called magnetoresistive phenomena [19].

Giant magnetoresistance (GMR) is a phenomenon observed in FM/NM/FM structures, where FM stands for ferromagnetic material and NM for nonmagnetic material. This phenomenon, which is part of the magnetoresistance family, is characterized by a change in the resistance of the structure in the external magnetic field [4, 9, 20]. The value of resistance of GMR structures depends on the direction of magnetization of adjacent ferromagnetic layers separated by a non-magnetic layer. The scattering of an electron moving through the structure depends on the correspondence of its spin and the direction of magnetization of the ferromagnetic layer [8]. The compatibility of the spin direction and the magnetization direction of the ferromagnetic layer results in less frequent scattering of the electron in the ferromagnetic layer as well as at the FM/NM interface than in the case of opposite directions of these vectors. Both of these configurations are shown in figure 1.

If the alternating ferromagnetic layers have the same direction of magnetization, the electron with conformal spin will be scattered less frequently, while the motion of the electron with opposite spin will be disrupted much more frequently [8]. The apparent result of this behavior is a decrease in the resistance of the structure relative to the configuration in which the alternating ferromagnetic layers have opposite resultant magnetization vectors [13]. These two states, referred to as parallel and antiparallel configurations, are shown in figure 1.

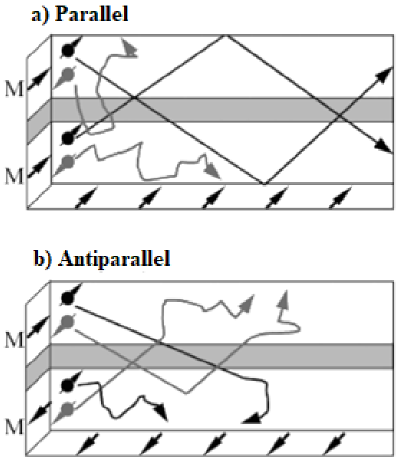

Fig. 1. Parallel (a) and antiparallel (b) configuration of FM/NM/FM structure exhibiting giant magnetoresistance phenomenon [3]

The thicknesses of the layers of structures exhibiting the giant magnetoresistance phenomenon are on the order of nanometers [16]. Such small sizes are crucial for the occurrence of this effect. The adequate thickness of the non-magnetic layer is particularly important; as its thickness decreases, an increase in the GMR effect is observed [2, 17]. For non-magnetic layer thicknesses on the order of a few nanometers, an oscillatory dependence of the exchange interaction is observed translating into an oscillatory nature of the phenomenon [10].

There are various realizations of structures exhibiting the phenomenon of giant magnetoresistance [20]. Additional layers and their thicknesses can significantly improve the desired magnetoresistance properties of a given sample. The basic one is the FM/NM/FM structure. It serves as the simplest possible explanation of the main mechanisms of the Giant Magnetoresistance phenomenon. These include multilayer FM/NM/FM structure, spin valve, pseudo spin valve, and granular alloys [5, 18]. Due to the current stage of development, only the basic FM/NM/FM designs are produced at this time.

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The aim of this study was to develop a fabrication technology for NiFe/Ti/NiFe MEMS structures and to perform DC resistance measurements under a strong magnetic field. As part of the presented work, two series of structures differing in the type of technological mask used were fabricated.

1. Magnetron sputtering

There are several ways of obtaining thin film-structures. They differ in the purity and homogeneity of the obtained layers, in the time required for the process, in the possibilities of sputtering different types of materials, and in the cost of the necessary equipment and the process itself [1, 6]. Structures exhibiting the phenomenon of giant magnetoresistance do not require technological processes requiring high temperatures, i.e. diffusion or implantation, to be produced, as compared to semiconductor components. Production of GMR structures, which can already serve as sensors of e.g. magnetic field strength, is relatively simple; just a few lithographic processes are enough to obtain a functional device [7]. A frequently used method is sputtering, which provides uniform coverage and high sample purity [15].

Magnetron sputtering is a type of ion sputtering. Ionized particles of noble gas, for example, argon, thanks to the high voltage applied in a high vacuum chamber, are bombarding the target, which is the source of the material. Bombarding causes the material particles to be knocked out and deposited on the desired substrate. The magnetron sputtering chamber is shown in.

Magnetron sputtering is characteristic of using an additional magnetic field under the target in the form of permanent magnets or electromagnets. The magnetic field at the source of the material causes the trapping of electrons above the surface of the target leading to an increase in ion density. This increases the efficiency of the entire sputtering process. Metallic materials, like ferromagnetic and non-magnetic layers in GMR structures, can be sputtered using the DC power supply of the magnetron [21].

The Kurt J. Lesker® NANO 36 sputtering system, which is at the disposal of the Department of Electronics and Information Technology of the Lublin University of Technology, was used to produce thin films.

2. Technology of thin-film GMR structures

Microscope slides were used as substrates for the structures. In the case of the first series, enclosures made by 3D printing were used as a technological mask. In the second series, kapton tape was used as a technological mask; the process sequence used is shown in figure 2.

The sputtering processes take place in a high vacuum chamber. Each individual process requires a change of target and re-adjustment of the sputtering chamber to the appropriate pressure level. The thickness of the resulting layer is monitored during the process, making it easy to adjust the sputtering length to the desired layer thickness. Permalloy NiFe was used as ferromagnetic material, while copper Cu was used as non-magnetic material [14]. A permanent magnetic field of neodymium magnets was applied along the long edge of each sample during the sputtering of ferromagnetic layers near the substrate [11, 22]. This procedure was intended to induce easy axis magnetization of these layers [12].

The sputtering process parameters for both series are shown in Table 1. All technological processes take place under a vacuum of 10^{-7} Torr.

The final dimensions of the structure are 20 mm × 2 mm and 65 nm of thickness. Using graphite glue, copper wires are attached to both edges of the structure. An additional plastic housing protects the sample from mechanical damage and makes it easier to carry out measurements (Fig. 3).

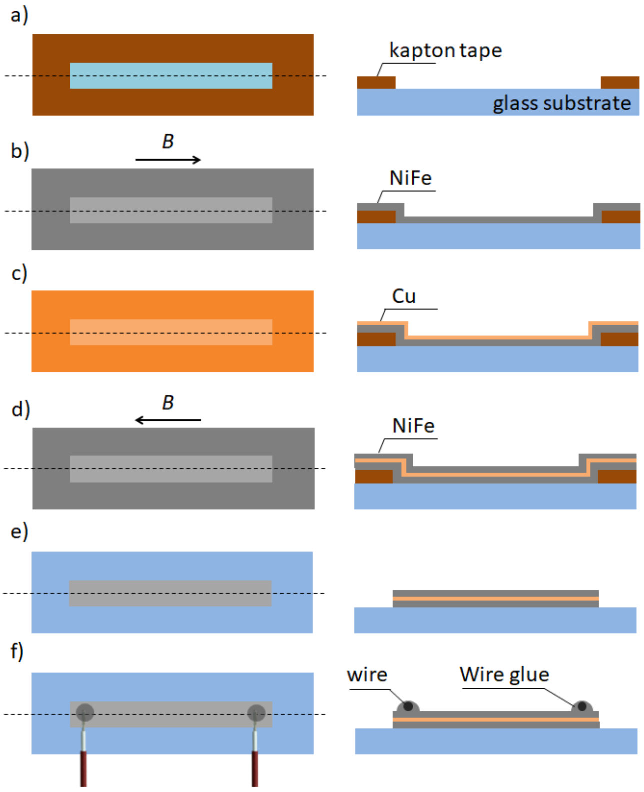

Fig. 2. Structure process sequence: (a) use of kapton tape as a technological mask, (b) deposition of a 30 nm NiFe layer in the presence of an magnetic field, (c) deposition of the 5 nm Cu layer, (d) deposition of a second 30 nm NiFe layer in the presence of an magnetic field, (e) removal of the kapton tape, (f) final structure

Table 1. Processes parameters

Lp.	Layer material and thickness	Plasma power Density [W/sq^2]	Argon flow rate [sccm]	Deposition time [min]
Series 1	NiFe (30 nm)	75	50	15
	Cu (5 nm)	50	40	3
	NiFe (30 nm)	75	50	15
Series 2	NiFe (30 nm)	90	85	15
	Cu (5 nm)	90	50	3,5
	NiFe (30 nm)	65	85	18

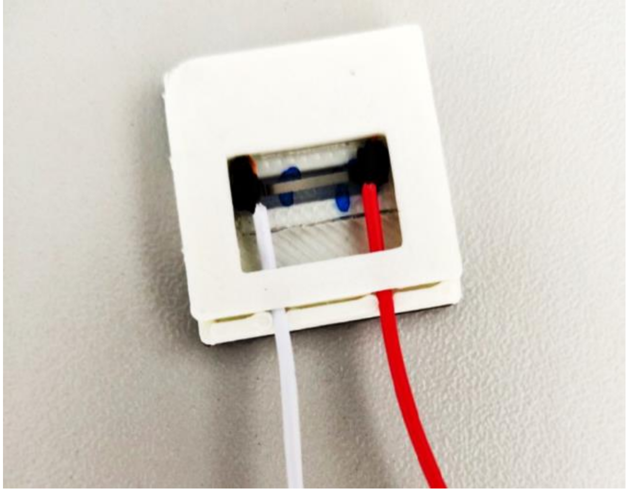

Fig. 3. Final structure in plastic protection

3. Experiment methodology and results

Samples of both series were measured for two-wire DC resistivity. These measurements were carried out using two strong neodymium magnets whose magnetic field induction was about 0.5 T, a KeySight 34410A multimeter cooperating with LabVIEW software, and a PC unit. These measurements consisted of alternating resistance measurements of the structure outside the magnetic field and in the magnetic field of the neodymium magnets. One hundred measurements were made alternately for each state. The longer edge of the sample is parallel to the external magnetic field lines of the neodymium magnets. Resistance measurement results for one of the samples of both series are shown in figure 4 and figure 5, respectively.

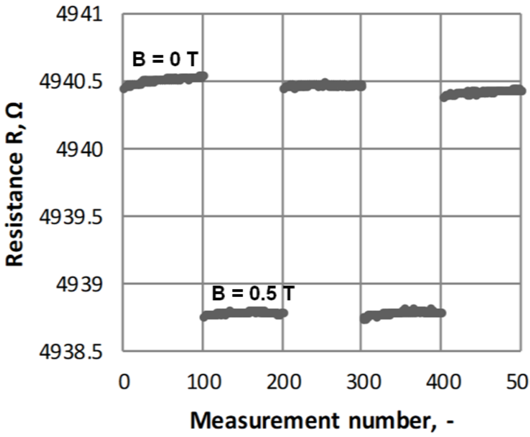

Fig. 4. Sample from the first series, NiFe(30)/Cu(5)/NiFe(30); plastic technology mask

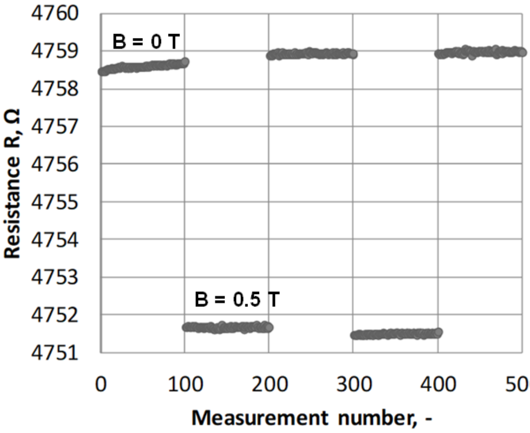

Fig. 5. Sample from the second series, NiFe(30)/Cu(5)/NiFe(30); technology mask made of kapton tape

The first one hundred measurements are made in the presence of a zero magnetic field induction. The measured resistance is therefore the resistance of the structure under the default conditions. Another hundred measurements were taken 5 seconds later when the tested structure was already between the plates of neodymium magnets. From both figures, it is possible to notice a decrease in the DC resistance of structure under the influence of a strong external magnetic field. In the case of the first series structure, this difference is about 1.7 ohm, while for the second – over 7 ohm. For the first sample, the decrease of the resistance in relation to the initial resistance is about 0.3‰ and for the second sample – about 1.6‰. In each of the states, with no magnetic field and strong magnetic field, the consecutive measurements do not seem to differ much from each other.

4. Summary

The performed measurements of the two-wire DC resistance of NiFe/Cu/NiFe thin structures in an external magnetic field seem to confirm the occurrence of the giant magnetoresistance phenomenon in them. In the case of the structures of both series, an apparent change in the sample resistance in a strong magnetic field is noticeable.

For the second series structure, the resistance difference between the two abdicated states is more than 7 ohms. The resistance changes of sample one are much smaller. It is suspected that this is due to the types of technology masks used. While the kapton tape adheres tightly to the substrate surface and marks the exact boundary of the sample, the 3D printing enclosures used are not certain to maintain sufficient contiguity. The applied method of mounting substrates in the created enclosures gives the possibility of uneven deposition of sputtered materials at the boundaries of the structure. This can result in unforeseen phenomena due to inhomogeneities in layer thickness and possible contacts between ferromagnetic layers. The boundaries of the fabricated structures under the naked eye appeared to have no clear boundary. It is possible that the use of uncertain plastic material in the sputtering chamber during the magnetron sputtering process affects the purity of the resulting films. Concerns arising from the previous use of additional enclosures as a process mask in the magnetron sputtering process result in the abandonment of the intention to use them in this role in future research. 3D enclosures as technological masks are not used because they require more effort and, as the present results indicate, their use does not result in the desired results. The use of kapton tape in this role on a larger scale of production in comparison to the photolithography method used also seems to be ineffective and is not used. This method can be used when making single runs of structures.

The measurement methodology was to observe the magnitude of resistance changes of the structures in a sufficiently strong magnetic field. It is impossible to obtain a complete characterization of the resistance changes as a function of the magnetic field induction in this way. We also do not know the saturation induction field of the structures in question, above which values the resistance changes are not observed.

The method used to fabricate thin-film structures exhibiting giant magnetoresistance appears to be correct. The developed technological sequence allows to obtain a series of samples exhibiting resistance changes in an external magnetic field. On the basis of the obtained results, it can be concluded that at the present stage the application of the kapton tape as a technological mask is satisfactory.

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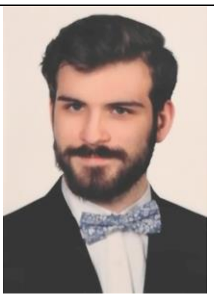

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