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Automatic Setup for Characterizing Structures Exhibiting Magnetoresistive Effects

Streszczenie. *W artykule opisano rozwój zautomatyzowanego systemu pomiarowego struktur cienkowarstwowych wykazujących efekty magnetorezystancyjne, takie jak magnetorezystancja anizotropowa i gigantyczna. System składa się z miernika rezystancji/impedancji oraz stołu do pozycjonowania próbek sterowanego oprogramowaniem Matlab. Podano szczegóły dotyczące konstrukcji systemu, w tym wykorzystania Arduino Nano do sterowania stołem pozycjonującym. Omówiono przykłady zastosowań w pomiarze zmian rezystancji w różnych orientacjach próbek.*

Abstract*. This article describes the development of an automated measurement system for thin-film structures exhibiting magnetoresistive effects, such as anisotropic and giant magnetoresistance. The system includes a resistance/impedance meter and a sample positioning table controlled by Matlab software. Details on the system's design, including the use of Arduino Nano for controlling the positioning table, are provided. Examples of application in measuring resistance changes in different sample orientations are discussed. (****Automatyczne stanowisko do charakteryzacji struktur wykazujących efekty magnetorezystancyjne****).*

Słowa kluczowe: magnetorezystancja, automatyzacja pomiarów, system pomiarowy, struktury cienkowarstwowe.
Keywords: magnetoresistance, automation of measurements, measurement system, thin-film structures.

Introduction

Automation of measurements is of great importance in research and development work, as it allows for the reduction of characterization and testing time of fabricated structures and minimizes the impact of human factors. This directly translates to a reduction in research costs [1, 2].

The automatic measurement system developed at the Department of Electronics and Information Technology at Lublin University of Technology is used for testing thin-film structures exhibiting magnetoresistive effects. It consists of a resistance or impedance meter and a stage that automatically positions the test sample relative to the vector of the external magnetic field. The entire measurement process is controlled by an application developed in the Matlab environment. The article describes the system and presents an example of its application. The authors' intentions regarding future work are also presented.

Motivation

The Department of Electronics and Information Technology at Lublin University of Technology conducts research aimed at developing technologies for structures exhibiting magnetoresistive effects. Understanding and controlling these phenomena in nanostructured materials is crucial for the development of modern magnetic sensors [3 –5].

Magnetoresistance (MR) is a commonly used term to describe the change in resistance caused by the presence of a magnetic field (MF) [2]. Many MR effects are known. An example is the anisotropic magnetoresistance (AMR) effect occurring in metallic ferromagnetic materials. The change in resistance depends on the angle θ between the direction of the applied magnetic field and the direction of the current flowing through the tested sample according to the relationship (1) [6, 7]

$$\rho = \rho_0 + \Delta\rho_{AMR} \cos^2 \theta \quad (1).$$

Typically, the resistance is lower when the electric current flows perpendicular to the direction of magnetization than when it flows parallel. The change in resistance (MR coefficient) due to the AMR effect is quite small, a few percent for the $Ni_{80}Fe_{20}$ alloy (permalloy) at room temperature, but this phenomenon is very useful in technical applications.

The Giant Magnetoresistance (GMR) effect [8, 9] is characterized by an increase in the resistance of thin multilayer structures F/(D/F)×n (F-ferromagnet, D-diamagnet, n-number of bilayer repetitions) due to the interaction of an external magnetic field with the structure. The change in conductivity arises from the scattering of electrons at the layer boundaries and depends on the relative alignment of the magnetization direction of the layers and the electron spin direction. Parallel magnetization directions usually result in lower resistance than when the magnetization directions are antiparallel [10, 11].

In a single technological series, approximately 100 test structures of the type F/(D/F)×n are produced, which, according to their layered construction, should exhibit GMR. All of them are tested for their response to the presence of an external magnetic field and the position of the structure relative to the magnetic field vector. To develop highly sensitive devices, it is necessary to characterize the fabricated elements. So far, measurements of the produced structures have involved determining the changes in resistance in the presence of a magnetic field of varying intensity, in three positions of the sample relative to the magnetic field vectors [12, 13].

Due to the time-consuming nature of characterizing structures resulting from a single production series and the necessity to expand measurements to include the effect of the sample's position relative to the MF, an automatic stage with a test structure holder was designed. This allows positioning at any angle and enables automatic measurements of electrical parameters. The developed stage can determine the direction of easy magnetization of the samples and the impact of magnetization anisotropy on AMR and GMR magnetoresistance phenomena, similar to [14]. The entire setup consists of several hardware and software components, which were developed at Lublin University of Technology and are detailed in this paper. The system's operation is described and illustrated with a practical example.

System stucture

The measurement system consists of the following components:

- a positioning table controlled by a programmable Arduino Nano platform,
- one of three meters used as needed: RuoShui 4090C, Keysight 34410A, or Hioki 3536,
- a PC with an application developed in the Matlab environment.

Automatic positioning table

The main component of the developed measurement station is an automatic table for positioning the structures under study in a magnetic field. The primary objective of this element was to ensure that the tested structure could be placed in any desired and precise position relative to the magnetic field lines. To prevent the table's operation from being disturbed by the strong magnetic field's influence on its electronic and mechanical components, while simultaneously minimizing the distortion of the magnetic field lines in the research area, the mechanical design had to be carefully planned. This required using a material for constructing the table that would not interfere with the magnetic field and ensuring that the electronic and metallic components were adequately distanced from the research area.

The table design accounted for the movement of each of the two axes using separate stepper motors. One of these motors was placed directly on the shaft responsible for rotating the table on one of the axes (Fig. 1, Fig. 2), and it was rotated through a gear transmission using the second motor. The movement of the table on the second axis is achieved through a V-belt and a 1:2 gear transmission (Fig. 3, Fig. 4). Both the shaft for one of the rotational axes and the gear transmission for the other allowed for the stepper motors to be positioned at a distance that ensures minimal interaction between the magnetic field and the table's electrical and metallic components.

The need to ensure the magnetic neutrality of the station required the use of appropriate materials for the mechanical structure. The components located in the research area do not contain any metal connecting elements. Additionally, the mechanical parts of the station located close to the magnetic field were made of polylactide (PLA) using 3D printing technology.

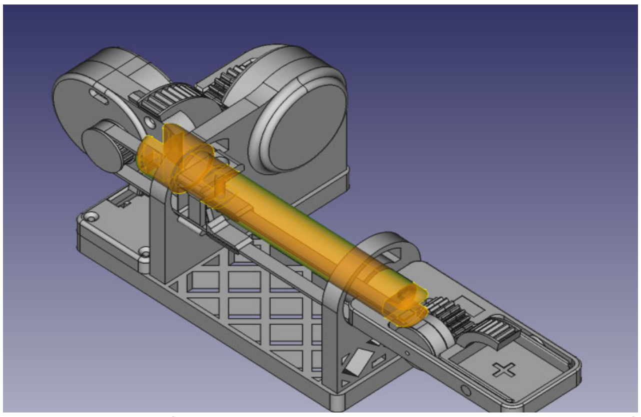

Fig. 1. Design of the automatic positioning table with the shaft structure responsible for rotating the stage in the Z–Y plane highlighted.

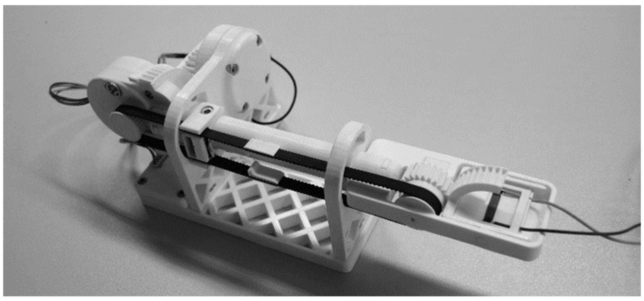

Fig. 2. Automatic positioning table.

For rotating the table in both axes, 28BYJ-48 stepper motors were used. These motors are characterized by their small weight and size, 5 V supply voltage, and low current consumption. These factors allowed them to be powered directly by the programmable Arduino NANO platform, which was used as the control system for the table. Additionally, a stepper motor driver was included, which was designed as a dedicated printed circuit board. This driver utilizes IRLML0060 MOSFET transistors as switching elements (Fig. 5). The gates of the transistors are connected with two resistors. One of these resistors, with a resistance of 2 kΩ, is used to prevent unwanted opening of the transistor channel during the system startup before the peripherals are initialized in the microcontroller. The designed system also includes circuits for handling limit switches responsible for blocking the table rotation beyond a specified angle (90° from the initial position in both directions).

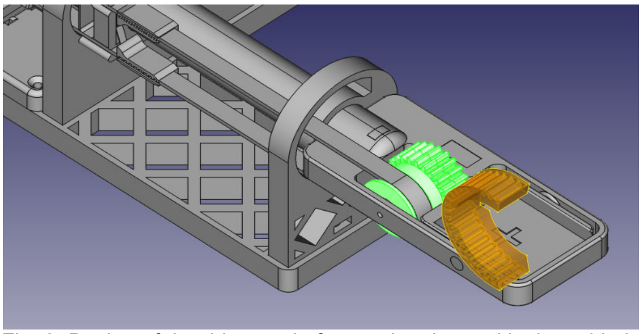

Fig. 3. Design of the drive mode for rotating the positioning table in the Z-X plane.

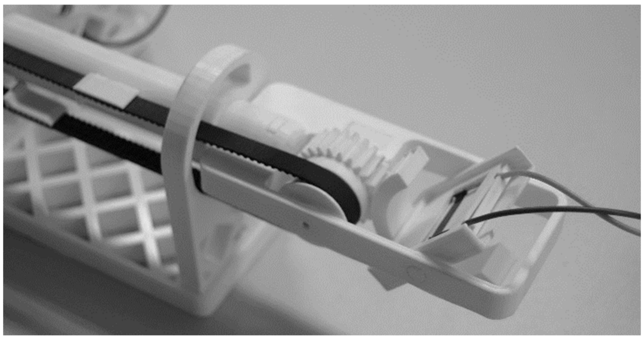

Fig. 4. Rotation of the positioning table in the Z-X plane.

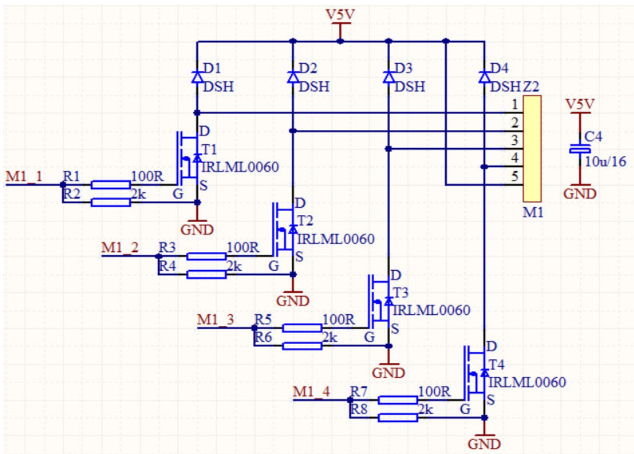

Fig. 5. Electrical schematic of the system designed in the CAD environment Altium Designer 6 for controlling a 5-wire stepper motor.

Test structure technology

The subject of the research was three-layer NiFe/Cu/NiFe structures, obtained by magnetron sputtering on two types of substrates: glass and Al_2O_3. The first NiFe layer, with a thickness of 100 nm, was deposited at a gas flow rate of 100 sccm and a plasma power of 100 W. The middle Cu layer, with a thickness of 30 nm, was deposited at a gas flow rate of 125 sccm and a plasma power of 150 W. The top NiFe layer, also with a thickness of 100 nm, was deposited at a gas flow rate of 139 sccm and a plasma power of 150 W.

To achieve the initial antiparallel magnetization state, two methods were used:

- an additional pinning layer made of an antiferromagnet (Cr) with a thickness of 30 nm, deposited at a gas flow rate of 250 sccm and a plasma power of 200 W (Fig. 6),
- an external magnet, which is generating a magnetic field directly at the site of the deposition of the first ferromagnetic layer.

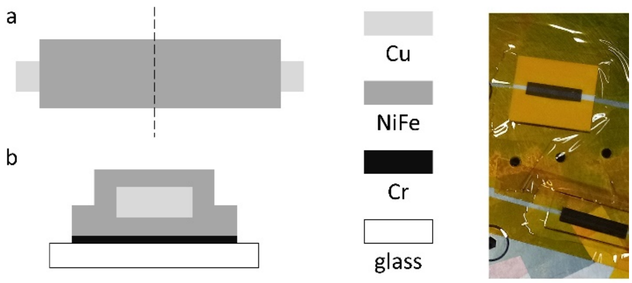

Fig. 6. (a) Schematic of NiFe/Cu/NiFe film, (b) cross-section of the structure, (c) photograph of the sample.

Measurement procedure

The measurement process is schematically presented in figures 7 and 8. In the first method, the measured structure (and simultaneously the current flow direction) is parallel to the MF vector (Fig. 7a). Then, the table is rotated by 90° along the Z-axis, positioning the sample perpendicular to the MF direction, as shown in Fig. 7b. The next step is to rotate the table in the opposite direction by 180° (Fig. 7c) and return to the initial position.

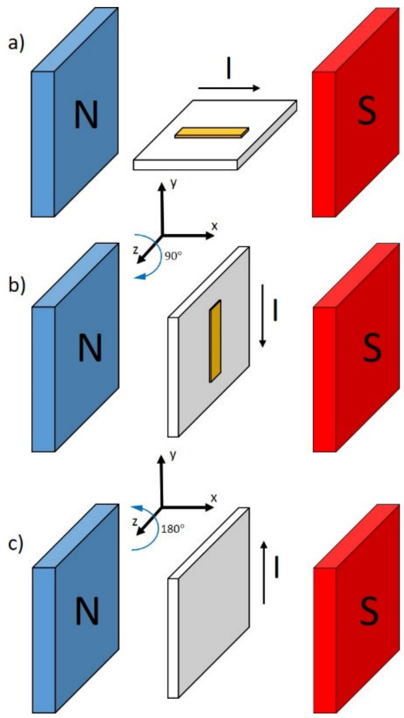

Fig. 7. Diagram of the application of a positioning table rotating around the Z-axis.

In the second situation, the table is rotated about the Y-axis (Fig. 8). In the initial position, the surface of the sample and the direction of current flow are perpendicular to the direction of the magnetic field lines (Fig. 8a). Then, the table is rotated by 90°. The side edge of the structure and the direction of current flow are perpendicular to the direction of the magnetic field lines (Fig. 8b). Next, the table is rotated 180° in the opposite direction (Fig. 8c) and returns to the initial position.

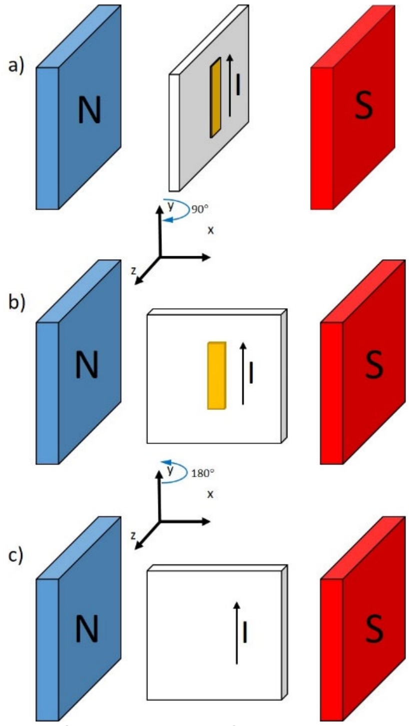

Fig. 8. Diagram of the application of a positioning table rotating around the Y-axis.

Example of data

The results of the resistance measurements using the positioning table are presented using the example of Cr/NiFe/Cu/NiFe structures on an Al_2O_3 substrate. Fig. 9 shows the dependence of resistance R on the angle θ of the sample position relative to the magnetic field lines during rotation around the Z-axis. It can be observed that the resistance of the sample is lowest in the initial position, i.e., when the surface of the sample and the direction of current flow are parallel to the magnetic field lines. Conversely, when they are perpendicular to each other, the resistance of the structure is highest. These changes are small, suggesting the presence of the AMR effect in the overall magnetoresistance of the tested sample.

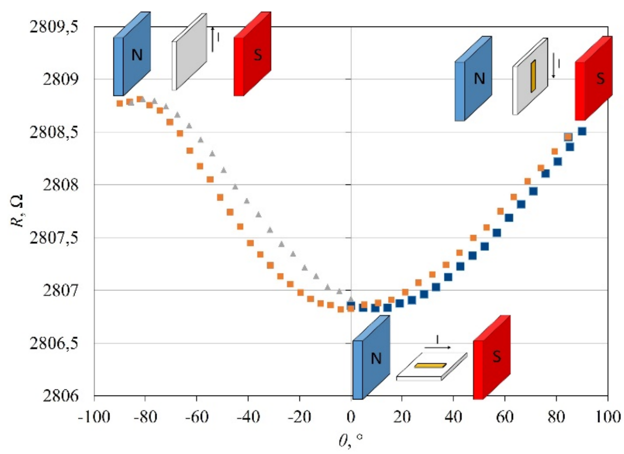

Fig. 9. The dependence of resistance R on the angle θ of the sample's position relative to the magnetic field lines during rotation around the Z-axis.

The second situation, where the sample is rotated around the Y-axis, is shown in Fig. 10. In this case, the highest resistance is obtained in the initial position when the surface of the structure and the direction of the current flow are perpendicular to the MF direction. Rotating the sample either left or right by 90° results in a decrease in resistance.

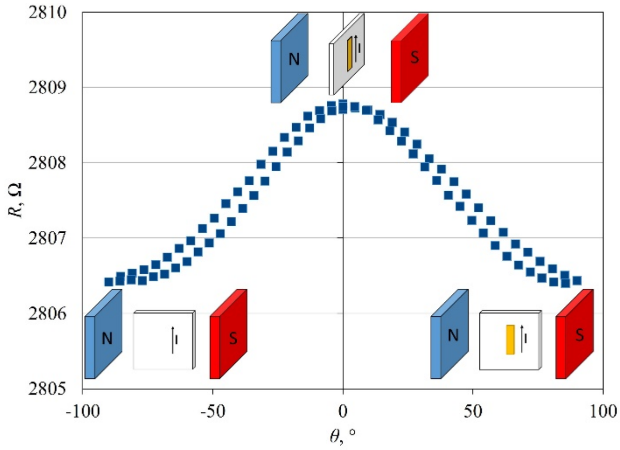

Fig. 10. The dependence of resistance R on the angle θ of the sample's position relative to the magnetic field lines during rotation around the Y-axis.

Summary

The paper is focused on the development and application of an automated measurement system designed for testing thin-film structures exhibiting magnetoresistive effects. It emphasizes the significance of automation in research and development activities, especially for reducing the testing duration of produced structures and minimizing human error, thereby lowering research costs. The automated measurement system consists of a resistance or impedance meter and a sample positioning table, which can precisely position the sample in relation to the external magnetic field vector. The entire measurement process is controlled via an application developed in the Matlab environment.

The authors are focused on developing technologies for structures exhibiting magnetoresistive effects like anisotropic and giant magnetoresistance. Understanding and controlling these phenomena in nanostructured materials are crucial for developing modern magnetic sensors.

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