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HABILITATION THESIS

SUMMARY

Contributions to the study of nanostructured magnetic systems for the development of sensors with applications in electrical engineering

Domain: Electrical Engineering

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This habilitation thesis presents the main scientific and professional achievements starting from PhD studies and the defence of my doctoral thesis entitled "Study of magnetic properties in multilayer structures", until these days.

Studies made on magnetic thin films and magnetic multilayers show interesting galvanomagnetic effects like Anisotropic Magnetoresistance (AMR), Giant Magnetoresistance (GMR) and Tunnelling Magnetoresistance effect (TMR) which have driven many technological developments. A consequence of the AMR effect is the Planar Hall Effect (PHE) which develops in magnetic thin films using a Hall effect configuration but with the magnetic field applied in the film plane. These effects are successfully used both for fundamental studies on magnetic thin films but, more important, for applications like magnetometers, current sensors, magnetic memories or detection of magnetic nanoparticles in lab on a chip applications.
In addition to structures developed in laboratories for fundamental and targeted studies, many commercial devices based on magnetoresistive effects can be found on the market. These help scientists to develop much more easily applications in electrical engineering like magnetometers that can detect magnetic fields down to μT and even lower, current sensing, energy monitoring, rotation sensors for automotive applications, magnetic compass and others.
When I began my doctoral studies in 1992, this was a relatively new field of research, and I thought I could bring valuable contributions to it.
This habilitation thesis is structured in *two main parts*. The first part presents the main contributions and scientific achievements obtained by the author. The second part presents the scientific and didactic development plan.

The first part consists of 5 chapters as follows:
Chapter 1 presents the main aspects of my scientific and didactical achievements.
After defending my PhD thesis, I had the opportunity to start fruitful scientific collaborations in the frame of some scientific research projects. This helped me to continue, at a new scientific level, the work done during the PhD studies. Also, I had the opportunity to acquire scientific equipment and to develop new research directions.
Such that I coordinated 14 research projects as partner from Transilvania University of Brașov (UTBv) or as project manager.
In the frame of these projects were made studies on (i) magnetic thin films and multilayers deposition, structural, magnetic and electrical characterizations, (ii) advanced micromagnetic simulations on such structures to develop some applications like (iii) magnetic field sensors, rotation sensors, detection of magnetic nanoparticles (MNPs) for Lab-on-a-chip (LOC) applications or (iv) non-contacting current sensors. Also, studies on graphene structures were

done in the frame of the project 597PED and a magnetic field demonstrator using vertical graphene-based FET structures was developed.
These studies were published in scientific journals and disseminated through communications at Conferences. Besides these scientific achievements, an important aspect was focused on human resources. Such that, I had the possibility to hire, in the frame of the Project 3PCCDI/2008, two young research assistants. They started PhD studies and contributed to the research activities in other projects that I coordinated. One of them has defended his PhD thesis in Electrical Engineering in 2024.
As a result of my scientific achievements, I have published 35 papers in ISI journals with impact factor, and more than 27 papers in Conference volumes, some of which are ISI or IEEE indexed. The h-index is 10 (WOS), 11 (SCOPUS) and 13 (Google Scholar).

Chapter 2 presents contributions to magnetic thin films depositions and characterizations. After a brief review of the most important deposition methods, there are presented the most important structures obtained during my research activities. The magnetic and galvanomagnetic properties of these structures were discussed in corelation with their structure and surface quality, obtained by Atomic Force Microscopy. Such that, were highlighted the limitations of the thermal deposition method in deposition of magnetic films thinner than 5 nm. Hall effect measurements were used in addition to magnetic and magnetorezistive measurements to have a complete view of the samples properties. An original method to control the anisotropy of soft magnetic thin films, which is subject to a patent request, is briefly presented. This method uses magnetic dopped polymeric nanofibers deposited on the film surface using electrospinning method.
Micromagnetic simulations were employed to give a better understanding of the magnetic behaviour of the magnetic structures used in these studies. An original method used to design the structures for simulations is presented and the results are discussed in relation with experimental data and samples microstructure. This method was used for further studies to develop rotation sensors and applications for magnetic nanoparticles detection. The results were published in scientific journals, books and book chapters.

Chapter 3 presents contributions to MR effects studies both from theoretical and experimental point of view. Anisotropic (AMR) and Giant magnetoresistance (GMR) effects were modelled by micromagnetic simulations to have a better understanding of these phenomena and compared with experimental data for different structures. It is shown that AMR and PHE can be used to find useful information about some parameters like the coercive and exchange biasing fields. Also, from these measurements, the peak-field, which describes the maximum field for which the PHE sensor delivers a useful signal is determined and is related to the structure, magnetic properties and the shape anisotropy. AMR and PHE experiments on disk-shaped sensors are presented. Two important applications are discussed: (i) development of a rotation sensor and (ii) detection of MNPs with PHE sensors using an original detection setup. This setup allows finding with precision the switching field in these structures and gives a highly sensitive method to detect MNPs, 1.87×10^{-5} emu or 1.1 μg of PEG6000 functionalised maghemite nanoparticles. Both micromagnetic and experimental activities were employed for these developments. As a result, a national patent about a rotation sensor was obtained.

The GMR effect was studied both using micromagnetic and experimental activities. Were simulated different structures that present particular field behaviour of the GMR effect and the agreement with experimental data was very good. For experimental measurements were used commercial integrated circuits (ICs) based on GMR structures. Is discussed how the GMR sensors are connected inside the chip and, by micromagnetic simulations, is discussed the role of the used magnetic field concentrator used to enhance the field sensitivity. We showed how can be linearized the field behaviour for sensing applications. More details on using such a GMR based magnetic sensor are presented in Chapter 4. Finally, a detailed analysis on thermal drift and noise in MR structures is presented. Some methods to mitigate these issues are discussed.

Chapter 4 presents contributions on development of a non-contacting current sensor using commercial GMR magnetic field sensors.

There were two implementations. Both are using *an original setup*, denoted by us in published papers, as double differential setup. This setup assures a very good thermal stability and immunity to external magnetic fields that alter the output signal. To implement this type of current sensor, an analytical model was developed that allows the calculation of the magnetic field created by the current that flows through conductive trace(s). The first implementation uses a simple U-shaped current trace above on which are placed two chips with GMR elements that are polarized by using a permanent magnet. With the help of a signal conditioning setup and a low-cost data acquisition board was implemented a non-contacting DC/AC measurement system with a sensitivity between 0.027 to 0.03 V/A. The system was proved to follow accurately the current wave form with a very low harmonic distortion. The detection limit is 10 mA in DC and 25 mA with a maximum applied current of 4 A.

The second implementation uses a similar setup but adapted for low current measurements. For this, a multi-turn U-shaped trace was used. By modelling this type of trace was found the optimal number of turns to be used, related to the experimental limitations. A pair of coils was used so that the optimal polarization field could be precisely adjusted. A sensitivity down to 23 mV/mA with a detection limit of 0.1 mA in DC and 0.2 to 0.3 mA in AC with a bandwidth of 10 Hz to 10 kHz were found. A maximum current of 300 mA can be applied through the current trace.

Chapter 5 presents contributions to the design, microfabrication and testing of a hybrid integrated circuit (IC) that uses exchange biased AMR elements connected in two Wheatstone bridges deposited on the same chip. A single mask was designed and used to deposit, by DC magnetron sputtering, the sensors and the viability of this approach was confirmed by micromagnetic simulations. A U-shaped current trace was directly printed on a thin Kapton layer (0.045 mm thick) that has been attached to the chip. Like in the previous reported implementations with commercial GMR sensors, this is a double differential measurement setup. By using a custom-built characterization system, the demonstrator chip was tested in lab conditions both for DC and AC current detection. The sensors show a sensitivity in magnetic field between 0.0165 to 0.0186 mV/(Oe·mA) with a very good linearity. The low limit of current detection is 2 mA both in DC and AC.
As mentioned, both in this chapter and in the published paper that presents these results, further improvements can be implemented. This study emphasizes the possibility of using direct printed circuit elements to simplify the design and implementation of other applications employing magnetic sensors.

The second part of this thesis presents the future scientific and didactic developments plan.
There are enumerated some of the new research topics to be developed like: applications with MR sensors for non-contacting monitor of residual currents in electrical installations and analysis of current wave forms in different electrical circuits, innovative methods to reduce the electrical noise in MR sensors, printed electrical circuits and MR sensors for industrial applications and wearable devices, non-contact monitoring of some critical components from power supply sources and others. Improved signal acquisition systems and advanced algorithms employing Machine Learning and AI will be used to collect and process data. Thus, doctoral students will be attracted to get involved in these interdisciplinary research topics. At the same time, will be consolidated the collaboration with partners from other research institutions and new applications for research projects will be prepared to get access to funding to sustain a high-quality level of the research activity and to improve the available research infrastructure. Such that, objectives like (i) improving the results of the research activity, (ii) gaining more visibility and (iii) improving the quality of the human resource involved, will be beneficial for the field of Electrical Engineering.
Teaching activity plays an important role in training high-quality engineers and attracting students for research activity. Such that, modern teaching methods will continue to be used to present, in an attractive way, phenomena and interesting applications in electrical engineering and other related fields.