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MAGNETIZATION PROCESSES DEPENDENT OF TIME AND TEMPERATURE IN NANOSTRUCTURED MAGNETIC SYSTEMS

- PHD THESIS SUMMARY -

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In recent decades, scientific research has undergone a remarkable development, supported by increased interest in what we call nanotechnologies, meaning miniaturization of electronic components used everywhere. Thus the ability to synthesize nanoscale physical structure of interest for various technological and experimental methods has evolved, allowing the exploration of physic-chemical properties different from the massive magnetic samples [1-5].

When discussing magnetic nanostructures, we must have regard to the distinctive properties of each isolate element and the effect of the whole interactions with other entities to which it belongs. Analyzed separately, each entity (nanowire, nanotube, nanoparticle) in the composite of nanostructures shows a shape anisotropy that favors preferential ordering of the magnetic moment in the absence of any external magnetic field. Under the action of an external magnetic field, the elements of a nanostructured array in which the interactions are negligible, switches only when overcoming the energy barrier induced by the intrinsic anisotropy. But this simple case is valid only if the constituents are at a considerable distance. The need of technology to make small structures lead to the condition of increasing the density of the useful elements, including magnetic ones For this reason interactions are essential to their behavior in external magnetic field.

The constant interest in the industry for magnetic storage devices is to achieve high storage spaces in a volume as small as possible. To achieve this goal, longitudinal magnetic media (axis of easy magnetization of the particles are parallel to the plane containing them) have been quitted, with the advent (2005 - Toshiba) of hard disk drives built by ordering the easy axis perpendicular to the substrate on which the array is built.

Longitudinal magnetic environment is still of interest both from a practical and fundamental research point of view [6-10] in the domain of condensed matter physics. Thus, in recent years a number of such arrays for nanostructured magnetic recording application have been developed [11] in the field of sensors and actuators and the high frequency electronics [12-15]. For example, from a fundamental perspective, longitudinal arrangement in frustrated configuration array more is very much studied [16-18].

The thesis aims essentially a systematic review of longitudinal ferromagnetic nanowire arrays.

In general, to explain the magnetization processes we use two types of models: physical and phenomenological. The physical implies the use of specific parameters in functions that describe the fundamental intrinsic behavior of material studied. For example, a widely used physical model in micromagnetism that describes the dynamic interaction of the magnetic moments under magnetostatic interaction, anisotropy, exchange interactions and the application of a magnetic field, is Landau-Lifshitz-Gilbert model (LLG). Each contribution is a term in the equation (LLG equation) assigned for each element (magnetic domain) in the array. This can mean very long simulation intervals for the analysis of macroscopic systems, so it becomes convenient to use phenomenological models, which although vague (the physical meaning of the parameters does not have consistency), may give similar results.

In this case we used a mixed model type Ising- Preisach in which the nanowires are characterized by a rectangular hysteresis cycle (histeron) - have intrinsic anisotropy (Preisach) and magnetization state of +1 or -1 (Ising) switching between states being mediated by a probability based on the energy barrier resulting (where there is the external field, coercivity, interaction field). The Preisach Model [19] is useful in describing the behavior of particles (nanostructures) taken as separate entities. It uses the assumption of the rectangular shape of the ferromagnetic hysteresis loop, which is true for a field applied in the direction parallel to the axis of easy magnetization. When the particles are taken together, should be considered the dipolar interactions. The Preisach Model allow, considering the interactions, that the hysteresis cycle become asymmetric but still rectangular.

A rigorous analysis highlights the limitations of the Classical Preisach Model (changing the state of a particle does not affect neighboring particles field of interaction, does not take into account the effects of temperature and the time of application of an external magnetic field, the speed of variation etc.), requiring the development of models that explain the experimental observations.

Relevant to this study is Moving Preisach Model [20] which involves consideration the real field applied to each particle as the sum of the external magnetic field and a term proportional to the magnetic moment within the system. This hypothesis gives physical consistency to the model for systems similar to longitudinal arrays in which the magnetic interactions can have magnetizing character or demagnetizing.

Ising model [21] is an attempt to simulate the physical structure of a ferromagnetic substance, his main merit being that it provides accurate solutions in certain cases. The classic Ising is applied to a system of spins to which are assigned two values / possible orientations (± 1), which interacts only with its two nearest neighbors, and with an external field. As we have proceeded in this study, you can attach a Monte Carlo model that can introduce time and temperature effects in the simulations.

The present study aims to continue the research conducted by the simulation / modeling group from the Faculty of Physics of Iasi in terms of nanostructured magnetic media arrays with longitudinal arrangement.

The proposed analysis takes and develops the new directions of investigating the switching field of each entity (nanowire) in the array, the application of sequences of magnetic fields (eg First-Order Reversal Curves - FORC), and assesses the contributions of these fields on FORC diagrams, obtaining consitent results in terms of highlighting new situations that can be studied in the paradigms of classical theoretical models.

Major hysteresis loop (MHL) is the most common way to characterize a magnetic material, the base from which most studies of magnetic materials starts. It provides information about the system, such as saturation magnetization, residual magnetization and coercive field of the sample. This is sufficient if only we need global data about a magnetic sample, but if the system is made up of separate entities, as the case of nanostructured arrays, then plotting curves of magnetization inside the major loop can provide additional data such as the distributions of coercivities and interactions of constituent particles.

FORC diagrams represents [22-23] a remarkable method of study complex structured materials such as magnetic nanowires systems with planar orientation. In such a distribution, the magnetostatic interaction may have either an magnetizing effector or a demagnetizing one, depending on distance values according to the two directions (along the direction perpendicular to the wires and in line with it). By controlling these geometrical constants (distances) one can dramatically alter the structure of interactions, as evidenced by FORC diagrams. It can thus be obtained in longitudinal array (through systematic observation of changes in FORC diagrams) a balance between the two effects, where they compensate each other, which have been studied in this paper.

Analyzing the relationship between switching events of individual entities on different reversing curves and the FORC diagram appropriate to chosen experiment, we have managed to establish a correspondence relevant to subsequent studies, between these rules of switching and the corresponding diagram.

Chapter I is a brief passage through models which will be referred throughout our study (Classical Preisach Model, Moving Preisach Model and the Ising Model). By combining the basic assumptions of these models resulted a scheme (Isin-Preisach Model) used to numerically simulate the magnetization processes occurring in the intimate structure of a nanostructured ferromagnetic material.

Chapter II is an introduction to the theory of magnetostatic interactions of dipoles and cylindrical wires uniformly magnetized and the motivation to simplify the calculus base by reducing the integral calculus given by the sum of magnetic fields charges from the bases of the cylinders to a rough calculation based on the assumption that the distance assessing the interaction effect is large enough to assume the uncompensated charge from the bases as concentrated in a point in the center of these disks, making the elements as dipoles.

Chapter III provides an introduction to the study and analysis of switching through FORC histograms in longitudinal array.

Chapter IV is an exhaustive analysis of switching processes in longitudinal arrays of nanowires through FORC curves. Basically, FORC diagrams are correlated with the structural changes imposed by particular experiment data. Given the representation method chosen to detect changes in the array, we built 2D longitudinal structures starting from the two 1D arrangements (in both directions of coordinate axes) to suggest the influence of two types of interactions (magnetizing, demagnetizing) on the assembly. Afterwords it was revealed an intermediate situation, where the magnetizing influence is compensated by the demagnetizing one, being performed an analysis of switching in a new coordinate system, highlighting differences between the two extreme cases (magnetizing/demagnetizing).

Chapter V assesses the changes occurring in FORC diagrams and individual particle switchings trajectories when faced with temperature and time variations.

General conclusions / elements of originality

• Longitudinal nanowire arrays have been studied (easy magnetization axis arranged parallel to the plane in which they are filed) using an Ising- Preisach type model;

• We have shown that interactions can have in this case a demagnetizing nature (the arrangement of wires favor the emergence of a magnetic field in the same direction as the magnetic moment of the particles, but different sense, destabilizing the state of magnetization of the elements in the array) or magnetizing (the alignment favors maintaining the magnetic moment of wires in the same direction), situation determined by the distance factor on the two coordinate directions Ox and Oy;

• We have simplified the calculation of the interaction field compared to the directly integrally (as in the perpendicular array), by considering the charge of the bases of the nanowires, dots, if the field from which the interaction is calculated is sufficiently far;

• We have constructed the 2D longitudinal array starting from the main 1D perpendicular or longitudinal array, so it can be observed by means of FORC diagrams, the influence of the two types of interactions;

• Varying the distances in both directions we have achieved a situation in which case FORC diagram is very similar to the classic model Preisach; switching paths reveals for low-coercivity wires, zero slope, the reversal positions on FORC curves oscillating around its own intrinsic coercivity. If the wires would have switched at the same value of the field, we could have obtained an unique contribution of a wire on the FORC diagram, aspect of scientific interest.

• Temperature and time plays a very important role both for the arrays where the longitudinal and perpendicular arrays, being established a method of determining the particles coercivity distributions with increasing temperature. We noted that in the case of longitudinal offset the FORC diagram retains its characteristics with increasing temperature and the trajectories of switching also have zero slope.

Scientific activity

Articles published or being elaborated

1. **Mihai Nica**, Alexandru Stancu

FORC diagram study of magnetostatic interactions in 2D longitudinal arrays of magnetic wires

Physica B – Condensed Matter, vol. 475, pp. 73 – 79, 2015

2. Radu Tanasa, **Mihai Nica**, Alexandru Stancu

Quantitative First-order Reversal Curve (FORC) study of interactions in 1D chains of magnetic wires

In course of elaboration.

3. **Mihai Nica**, Alexandru Stancu

Study of the individual magnetic wires switchings in 2D interacting wire arrays as a function of the system temperature

In course of elaboration + oral presentation at ***Joint MMM - Intermag Conference ianuarie 2016, San Diego, SUA.***

Papers presented at scientic meetings

[1] Mihai Nica, Alexandru Stancu

FORCs in 1D and 2D Longitudinal Arrays with Magnetizing, Demagnetizing and Frustrated Interactions

IEEE ROMSC 2014, ROMANIA IEEE Magnetics Society Chapter, Romania Section, Iasi, Romania, iunie 2014 – ***prezentare orală***

[2] Mihai Nica, Alexandru Stancu

FORC diagrams for 1D and 2D longitudinal arrays of nanowires

International Conference on Physics of Advanced Materials (ICPAM-10) Iasi, septembrie 2014 – poster

[3] Mihai Nica, Alexandru Stancu

Tracking interaction field intensity with FORC diagrams in longitudinal 1D, 2D arrays of magnetic wires and in frustrated systems

59th Annual Magnetism and Magnetic Materials (MMM), noiembrie 2014, HONOLULU, HAWAII – poster

[4] Mihai Nica, Alexandru Stancu

FORC diagram study of magnetostatic interactions in 2D longitudinal arrays of magnetic wires

The International Symposium on Hysteresis Modeling and Micromagnetics(HMM), mai 2015 - poster

[5] Alexandru Stancu, Costin Dobrota, Mihai Nica, Laurentiu Stoleriu

Evidencing the contribution of individual physical entities on the FORC diagram of a system of interacting macrospins

20th International Conference on Magnetism, Barcelona, iulie 2015 – poster

[6] Mihai Nica, Alexandru Stancu

2D Longitudinal Magnetic Nanostructured Systems

IEEE ROMSC 2013, ROMANIA IEEE Magnetics Society Chapter, Romania Section, Iasi, Septembrie 2013 – poster.

[7] Mihai Nica, Alexandru Stancu

Ising-Preisach model for time and temperature effects in magnetic nanostructured systems

The 6th International Workshop on Multi-Rate Processes and Hysteresis, MURPHYS 2012, mai, 2012, Suceava – România – poster.

[8] Mihai Nica, Alexandru Stancu

Time and temperature effects in magnetic nanostructured systems

Şcoala de vară IEEE Magnetics Society, Chennai, India, 22-27 iulie 2012 – poster.

[9] Mihai Nica, Alexandru Stancu

Time and temperature effects in magnetic systems studied with Ising-Preisach model

Joint Conference COST MPO904 Action & IEEE ROMSC 2012, Iaşi, septembrie 2012

[10] Mihai Nica, Alexandru Stancu

Magnetisation processes in magnetic nanostructured systems

IEEE ROMSC 2011, ROMANIA IEEE Magnetics Society Chapter, Romania Section, Iasi, Octombrie 2011 – poster.

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