

Appendix No 2 *to the Maria Tekielak Application for the commencement of the Habilitation Procedure*

Abstract of the habilitation thesis

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2.1 First name and family name: Maria Tekielak

2.2 Diplomas and scientific degrees

Master's degree

Warsaw University, Branch in Bialystok, Faculty of Mathematics and Physics, 1983.

The Master thesis entitled "*Magneto-optical analysis of magnetic after-effect in garnet layer $Y_2Ca_1Fe_{3.9}Co_{0.1}Ge_1O_{12}$* " performed in Laboratory of Magnetism, Warsaw University, Branch in Bialystok (currently Department of Physics of Magnetism, University of Bialystok) under the supervision of Prof. dr hab. Andrzej Maziewski

Doctor of Science degree

Institute of Physics, Polish Academy of Sciences, 1998.

The Doctor thesis entitled "*Magnetic anisotropy and phase transitions connected with magnetization reorientation in cobalt-doped thin garnet films*" performed under the supervision of Prof. dr hab. Andrzej Maziewski.

2.3 Information of employment in scientific institutions

- 1984-1985** Trainee, Computer Centre, Department of Physics, Warsaw University, Branch in Bialystok
- 1985-1989** Senior Technical, Laboratory of Physics of Magnetism (currently Department of Physics of Magnetism), Department of Physics, Warsaw University, Branch in Bialystok
- 1990-1991** Specialist, Department of Physics, Warsaw University, Branch in Bialystok (since 1991 Institute of Physics, Warsaw University, Branch in Bialystok)
- 1992-1994** Science Technical Specialist, Institute of Physics, Warsaw University, Branch in Bialystok
- 1995-1998** Senior Science Technical Specialist, Institute of Physics, Warsaw University, Branch in Bialystok (since 1997 Institute of Physics, University of Bialystok)
- since 1998** Assistant Professor (adiunct), Institute of Physics, University of Bialystok (since 1999 Institute of Experimental Physics, University of Bialystok, since 2008 Department of Physics, University of Bialystok)

2.3 Indication of the achievement of habilitation procedure

The academic achievement resulting from Article 16 Paragraph 2 of the Act of 14th March, 2003 about the academic degrees and academic title submit for habilitation procedure is one-subject series of publications consisting of 9 papers. The theme of this series is "*Magnetization processes and magnetic domain structures in different nanostructures – from single layers to multilayers*".



2.4A. List of works that constitute a basis for habilitation procedure

- H1. M. Tekielak, Z. Kurant, A. Maziewski, L.T. Baczewski, A. Maneikis, A. Wawro,
Anisotropy of magnetic domain wall orientation in ultrathin Co grown on Mo(110) buffer layer,
Journal of Magnetism and Magnetic Materials 290, 783 (2005)
- H2. W. Stefanowicz, M. Tekielak, W. Bucha, A. Maziewski, V. Zablotskii, L.T. Baczewski,
A. Wawro,
Dendritic domain structures in ultrathin cobalt films,
Materials Science – Poland 24, No. 3, 783 (2006)
- H3. W. Dobrogowski, Z. Kurant, A. Nedzved, W. Stefanowicz, M. Tekielak, L.T. Baczewski,
A. Wawro, A. Maziewski,
Image processing study of ultrathin cobalt domain structure evolution induced by overlayer structure,
Materials Science – Poland 25, No. 2, 405 (2007)
- H4. Z. Kurant, R. Gieniusz, A. Maziewski, M. Tekielak, W. Stefanowicz, I. Sveklo, V. Zablotskii,
A. Petroutchik, L.T. Baczewski, A. Wawro,
Changes in magnetic properties of ultrathin cobalt films as induced by Mo, V, Au overlayers,
Journal of Magnetism and Magnetic Materials 316, Issue 2, e511 (2007)
- H5. P. Mazalski, I. Sveklo, M. Tekielak, A. Kolendo, A. Maziewski, P. Kuświk, B. Szymański,
F. Stobiecki,
Magnetic properties of (Co/Au)_N multilayers with different number of repetition N,
Materials Science – Poland 25, No. 4, 1289 (2007)
- H6. M. Tekielak, R. Schäfer, J. McCord, A. Maziewski, V. Zablotskii, L.T. Baczewski, A. Wawro,
Needle-like domain structure in Co films deposited on Mo (110),
Journal of Magnetism and Magnetic Materials 316, Issue 2, 184 (2007)
- H7. M. Tekielak, P. Mazalski, A. Maziewski, R. Schäfer, J. McCord, B. Szymański, M. Urbaniak,
F. Stobiecki,
Creation of out-of-plane magnetization ordering by increasing the repetitions number N in (Co/Au)_N multilayers,
IEEE Transactions on Magnetics 44, No. 11, 2950 (2008)
- H8. M. Tekielak, M. Dąbrowski, M. Kisielewski, A. Maziewski, V. Zablotskii,
Magnetic states and magnetization reversal in magnetostatically coupled multilayers with low perpendicular anisotropy,
Journal of Applied Physics 107, 083911 (2010)
- H9. M. Tekielak, R. Gieniusz, M. Kisielewski, P. Mazalski, A. Maziewski, V. Zablotskii, F. Stobiecki,
B. Szymański, R. Schäfer,
The effect of magnetostatic coupling on spin configurations in ultrathin multilayers,
Journal of Applied Physics 110, 043924 (2011)

2.4B. Presentation of the scientific works and achieved results

The main subject of the series of publications, giving rise to the habilitation procedure, is magnetic properties of different magnetic nanostructures, based on an example of cobalt layer with different number of repetition (multiplicity): from a single layers to multilayers. A particular attention to the spatial distribution of magnetization ordering of magnetization, magnetic phase transitions connected with reorientation of magnetization, magnetic domain structure and magnetic coupling between layers, was paid in these studies. These problems, of fundamental importance for physics of ultrathin materials, have not been studied deeply enough so far.

Properties of the magnetic nanostructures strongly depend on both the interface structure and the strains in magnetic layer, the latter caused, among other things, by lattice constant mismatch in nearest neighbouring layers. A large part of atoms of one kind, located in the layer surface, is a neighbour of another kind of atoms, forming structures with reduced dimensionality. The symmetry breaking induces modification of the electronic structure, as a consequence, lead to changes in magnetic properties. In the presented series of papers, some examples of the magnetic ordering modifications, by changing the environment of ultrathin layers, namely by changing both the coating layer (at the atomic scale) and the buffer layer structures, including their orientation, will be given.

When one describes magnetic properties of ferromagnetic material, it is conveniently to use the quality factor Q - a nondimensional parameter defined as the ratio of the magnetic anisotropy energy to be gained by a magnetization along the easy axis perpendicular to the sample surface, and the magnetostatic energy of a uniformly magnetized layer along the surface normal. The Q parameter strongly depends on the thickness of the magnetic nanostructures. Two reorientation of the magnetization (RPT) can be observed by changing the thickness of ferromagnetic layer. In a ferromagnetic material, with a thickness of the order of single atomic layers, a very large contribution to the surface magnetic anisotropy causes the out-of-plane ordering of magnetization. The reorientation to the in-plane magnetization direction (RPT-1) occurs, at a certain critical value d_{RPT1} (in the case of cobalt layers equal to around $d = 2$ nm), while the thickness increase. Usually it is assumed, that $Q(d_{RPT1}) = 1$. For further increase of the thickness, the magnetic domains, with a large out-of-plane component of the magnetization, arise in the volume of the layer, which means the reorientation of the out-of-plane state (RPT-2). In the case of cobalt layer, the RPT-2 occurs at a thickness of about $d = 30$ nm.

The different X/Co/Y single layer systems (where X and Y stand for nonferromagnetic layer of molybdenum (Mo), gold (Au) or vanadium (V)) and multilayers $[\text{Au/Co}]_N$ (where N means the number of repetition) are the objects of the presented cycle of papers. Magnetic nanostructures, consisting of single layer with different configurations, have been produced by molecular beam epitaxy in ultra high vacuum at the Institute of Physics, Polish Academy of Sciences in Warsaw. This was a series of both flat and wedge-shaped samples. The multilayers were prepared using magnetron sputtering technique in argon atmosphere at the Institute of Molecular Physics, Polish Academy of Sciences in Poznań. Both the process of growth of layers and the chemical composition of samples were monitored *in-situ*, using standard techniques, such as RHEED (Reflection High-Energy Electron Diffraction), LAXRD (Low Angle X-Ray Diffraction) and AES (Auger Electron Spectroscopy).

In the majority, the magnetic and magneto-optic *ex-situ* investigations were performed at the Department of Physics of Magnetics, University of Białystok. The analysis was performed using different experimental techniques, such as: (i) the high-resolution polarizing magneto-optical Kerr microscopy in both polar and longitudinal configurations, with the possibility of the vectorial analysis of magnetization components for different orientation of external magnetic field, (ii) magneto-optic Kerr magnetometry in three basic configurations



(polar, longitudinal and transversal), (iii) Magnetic Force Microscopy MFM, (iv) Ferromagnetic Resonance Spectroscopy FMR, and (v) Vibrating Sample Magnetometer VSM.

For the spatial analysis of the magnetic state, in the whole area of the sample, a special method of remanence imaging was developed, consisting of the registration (using a polarizing magneto-optical Kerr microscopy) of two images of the sample surface, successively reversed by perpendicular external magnetic, and then their differentiation. As a result, after applying an external magnetic field with the amplitude sufficient for the homogeneous magnetization of the whole sample, an image of remnant magnetization state was obtained. This method is particularly useful in the case of more complicated spatial configurations of layers with varying thickness (e.g. wedge-shaped), in which the classical (bulk) magneto-optical techniques are not effective. Unique opportunities of the application of this method should be also noted, for example, during the magneto-optical characterization of the layers during their *in-situ* manufacturing.

The modelling of local magnetization distributions, based on the OOMMF software (The Object Oriented Micro Magnetic Framework) for micromagnetic simulation, was carried out parallelly to the experimental studies.

Two main parts: the results, obtained for the structures containing a single layer of cobalt [H1-H4, H6] and the results for the multilayers [H5, H7-H9], are separated in the presented description of the cycle of papers. In the case of one layers study, the main objective was the explanation of the mechanisms of influence of ferromagnetic buffer and covering layers parameters, such as thickness, morphology and chemical composition, on the magnetic properties of ultrathin cobalt layer. The change of either the thickness of magnetic layer or both structure and thickness of the surrounding layers, can induce strong changes in magnetic anisotropy. This, in turn, may result in reorientation of the magnetization and in drastic changes of the size of domain structure, or in the existence of preference of domain wall orientations. A series of presented papers includes some examples of modifications of magnetic ordering by changing environment of ultrathin layers, it means, by changing the structure of its both coverage (at the atomic level) and the buffer layer structure, including their crystallographic orientation. These results represent a starting point for the analysis of magnetization processes in systems of multilayers, which is very important for understanding of the nature of interlayer magnetic interaction and its influence on both local and spatial magnetic ordering.

In the paper [H1], the results of the study of both magnetic domain structures and magnetization processes in Mo/Co/Au layers, are presented. Using the method of remanence imaging as a function of the out-of-plane-oriented external magnetic field it was shown, that in the range of cobalt thickness $d = 0.5-1.0$ nm, the perpendicular component of magnetization exists, while above this thickness, the reorientation of magnetization to the layer plane occurs. The studies of the domain wall localization during demagnetization processes, performed in the region of the existence of perpendicular component of magnetization, allowed determining the dependences of coercivity field on the thickness of cobalt layer. The two following mechanisms of the magnetization processes have been observed, in the presence of the out-of-plane oriented external magnetic field, as a function of the thickness of cobalt layer: the nucleation of new domains (for the two following ranges of cobalt thickness: $d \approx 0.5$ nm and $d \approx 1$ nm with low coercivity field values) and propagation of domain walls in the range of thickness of high-coercivity cobalt, about $d = 0.7$ nm. The presence of a strong uniaxial anisotropy in the layer plane was also found. This anisotropy affects both the layer magnetization process and the preference of the orientation of magnetic domain wall. The analysis of the RHEED results showed, that the Mo(110) buffer layer, deposited on sapphire substrate with (11-20) orientation, shows a strong distortion along the [001] direction. Therefore, in the Co (0001) and Mo (110) layers, a change of the effective

anisotropy constant, with a significant contribution to the magnetoelastic anisotropy, occurs. In this case, the direction of the preference of magnetic domain walls orientation coincides with the Mo[001] direction.

The investigations of the magnetization processes were continued in layers with similar configuration (Mo/Co/Au), but in a greater range of the thickness of cobalt wedge ($d = 5\text{--}50$ nm), where magnetization in a layer plane is oriented [H6]. The dependencies of coercivity field on both the cobalt layer thickness and the in-plane oriented external magnetic field direction, determined for different cobalt layer thicknesses, exhibit a maximum, which corresponds to the hard magnetization axis orientation, parallel to the Mo[1-10] crystallographic direction. However, the easy magnetization axis direction corresponds to the Mo[001] crystallographic direction. A magnetic domain structure with a needle-like shape and in-plane oriented magnetization was observed. The orientation and size of these needles were dependent on both the thickness of the cobalt layer and the direction of the in-plane oriented external magnetic field. For smaller thickness of the cobalt layer ($d = 15$ nm), the molybdenum layer strongly influences to the orientation of the magnetic domain walls. For larger Co thicknesses, the orientation of the domain walls depends on both the orientation of the easy magnetization axis and the direction of the external magnetic field, applied in the aim to produce the domain. Above a certain critical thickness, d_{RPT2} , the orientation of domain walls depends on the direction of the external magnetic field, only.

A special digital image technique was developed to the analysis of the shape and orientation of magnetic domain structure. The extraction, processing and analysis of images of the magnetic domain structure were performed with the original software, based on the LabView. The algorithm for digital image processing of the needle-like magnetic domains in ultrathin cobalt layers was proposed. This algorithm is based on the transformation of the needle-like objects into a binary array, and then, on the calculation of their geometric parameters. This procedure has been proven to be very useful to determine the preferences of the orientation of magnetic domain walls, caused by various factors, such as: the magneto-crystalline anisotropy, stress, vicinal surface and applied external magnetic field.

The influence of a nonferromagnetic cover layer on the changes of both magnetic anisotropy and magnetic domain structures in ultrathin cobalt wedge layer, with the thickness $d = 0\text{--}2$ nm, was studied with the use of the system X/Co/Y (where X, Y = Mo, V, Au) [H4]. The studies were performed as a function of the thicknesses of both the ferromagnetic layer and the cover layer. The analysis, performed with the use of remanence imaging method, showed, that the thickness of cobalt, at which the reorientation of magnetization from easy magnetization axis (perpendicular to the sample plane) to the easy plane occurs, depends on the type of the nonferromagnetic cover layer. A non-equivalence of the Mo/Co and Co/Mo interfaces was observed. The in-plane magnetic anisotropy is weaker, when the covered layer consists of molybdenum, which is associated with the pseudomorphic growth of Mo layer on the cobalt. As a result, weaker deformations in the cobalt layers (in comparison to the cobalt grown on Mo buffer) arise and/or, in consequence, different electron structures in interfaces occur. In the case of vanadium coverage, a small thickness of this material (0.1 nm) is sufficient for complete reorientation of magnetization. Such a strong influence of vanadium coverage can be explained by the change of the magnetic ordering of Co/V interface. The magnetic moment, induced on the vanadium surface, is antiferromagnetically coupled with respect to cobalt, thus both spin and orbital moment of the cobalt are reduced.

Some differences in magnetic domain structures, induced by V and Mo coverage layers, were observed. The nucleation mechanism dominated near the reorientation transition, while for thinner cobalt layer – the domain walls propagation one. The size of domain was strongly dependent on the cobalt layer thickness and was decreased by several orders of magnitude (down to submicron scale), when the cobalt layer thickness increased up to a value corresponding to the thickness of magnetization reorientation. The analysis of the remnant

images revealed the existence of the preference of growth direction of the magnetic domain structure in Au/Co/Mo system and their absence in the case of Au/Co/V one.

The analysis of the evolution of domain structure as a function of the ferromagnetic material has shown, that near the reorientation of magnetization, a reduction of the period of domain structure is going on. The paper [H2] presents the study of the ultrathin Au/Co/Au system, with such a cobalt layer thickness ($d = 1.5$ nm), which is slightly smaller than the thickness, at which the reorientation of magnetization from the out-of-plane state to the in-plane one occurs. The layers are characterized by a rectangular hysteresis loop with a strong perpendicular anisotropy and the occurrence of magnetic after-effect. The magnetization reversal process proceeds initially by the domain nucleation, and then, by the propagation of the domain walls with the dendritic character. The parameters of this process, such as the domain tip radius and the surface density the domain wall energy, were determined.

Similar domain structures were analysed in the paper [H3] in ultrathin cobalt layers with Au/Co/X structure (where X means either V or Mo), grown on sapphire substrate. At different stages of the magnetization reversal process, images of magnetic domain structures were registered, and then the topology properties were determined. The procedure of the determination the characteristic parameters of dendrite structures were proposed. Both the size of domains and the mean width of dendrites decreases while approaching to the thickness corresponding to the magnetization reorientation. A preferential orientation of domain walls in ultrathin Co, covered by Mo, but not by V, was found. This is due to, probably, the existence of a strong in-plane uniaxial anisotropy, induced by the molybdenum layer.

The magnetostatic interaction and its influence on both the magnetic ordering and magnetization processes in magnetic multilayers, was studied in papers [H5, H7-H9]. In general, the spatial distribution of magnetization and magnetization processes depends on many parameters, such as: number of repetition N , thickness of ferromagnetic layer, thickness of non-ferromagnetic spacer, and magnetostatic coupling between the layers. The presented results were obtained for $(\text{Co}(d)/\text{Au})_N$ multilayers, it means N -times repeated the sequence of ultrathin cobalt layer and gold spacer. Generally, for the thickness of spacer of a few atomic distances, neighbour ferromagnetic layers can interact both magnetostatically and by exchange. For suitably chosen, large enough thickness of nonferromagnetic spacer, only magnetostatic interaction plays a significant role. The presented results concern just this latter case.

Preliminary results of studies of multilayers $[\text{Co}/\text{Au}]_N$ and $[\text{Py}/\text{Au}/\text{Co}/\text{Au}]_N$ ($\text{Py}=\text{Ni}_{80}\text{Fe}_{20}$), with number of repetition N varying from 1 to 15 and with different thicknesses of cobalt layer ($d = 0.6\text{--}1.5$ nm) and gold layer ($d_{\text{Au}} = 1.5\text{nm}, 3\text{nm}$), were presented in the paper [H5]. All multilayers were characterized by the out-of-plane oriented easy magnetization axis. A strong influence of both the number of repetition and the cobalt layer thickness on both the magnetic domain structure and magnetization processes was observed. With the increase of N , the following effect were observed: evolution of geometry of magnetic domain structures, reduction of the domain period (down to the submicrometer size), increase of saturation field, and increase of nucleation field from a negative value (for small N with a rectangular hysteresis loop) to a positive value for large N . While the number of repetition increases over $N = 12$, an increase of the perpendicular component of magnetization is observed. An increase of the domain structure period as a function of the thickness of gold layer was also observed.

An introduction of Py layers led to shielding of the magnetic field of neighbouring cobalt layers and to the increase of the thickness of separating layers. Magnetostatic coupling between cobalt layers became weaker, thus, sequential layer-by-layer magnetization reversal process was observed. This effect was illustrated as both the presence of domains with multiple shades of grey and jumps in the hysteresis loop.

The analysis in a wider range of thickness of cobalt layer was carried out in the paper [H7], where cobalt has been studied with the thickness both smaller than d_{RPTI} ($d = 1$ nm) and greater than d_{RPTI} ($d = 2$ nm, $d = 3$ nm). In the first case, an increase of the number of repetitions N caused a drastic reduction of the size of domain structure and a change of the character of magnetization curves, i.e. a transition from hard to soft magnetically material. However, in the second case (for thicker cobalt layers $d = 2$ nm, $d = 3$ nm), where in a single layer magnetization was in-plane oriented, an increase in N , domain structure with perpendicular component of magnetization induced.

The aim of researches reported in the paper [H8], was to show the spatial distribution of magnetization in each layer of magnetostatically coupled system $(F/NF)_N$, (where F denotes a ferromagnetic layer, NF – nonferromagnetic one). The study was performed both theoretically and using micromagnetic simulation. The evolution of the spatial distribution of magnetization in a large range of changes of parameters Q and N - from the simplest case of a single layer, through double layer to multilayers, was analyzed. It was shown, that the range of the out-of-plane magnetization state existence could be extended to $Q < 1$ by proper choice of both N and the layers thicknesses. The role of interlayer magnetostatic coupling in the formation of both vortex-like and sinusoidal-like distributions of the magnetization was revealed. Different states of magnetization were illustrated in the phase diagram, (Q, N) . It was shown that weakly-anisotropic, magnetostatically coupled multilayers $(F/NF)_N$, are magnetically soft systems with low saturation fields, in which the domain size can be changed by several orders of magnitude due to small changes of Q , N , and/or thickness of the nonferromagnetic spacer. In the case of a two-layer system, the critical value of the quality factor Q at which the magnetization reorientation occurred, was determined (with good agreement) by both simulation and analytically. The reorientation of the magnetization followed for a much smaller value of Q parameter, unlike the single layer. It was also proved, that in the case of $N = 2$, the magnetostatic coupling disappears for the spacer thickness comparable to the domain size.

The objects of experimental analysis enriched by micromagnetic symulations, presented in the paper [H9], were ultrathin multilayers $(Co/Au)_N$ with both in-plane and perpendicularly oriented magnetic anisotropy. An analysis of magnetostatic interaction was performed for a given, fixed geometry of the system (i.e. $d = 3$ nm and $d_{Au} = 3$ nm) in a wide range of Q and N parameters, and in two following configurations of external magnetic field: either in-plane or perpendicular to the surface of the sample. As a result of micromagnetic simulations, supplemented by both measurements of magnetic parameters and visualization of domain structure, a three-dimensional reconstruction of the magnetization distribution in multilayers was made. It was shown, that in the range of magnetization reorientation (characterized by $0 < Q < 1$) the vortex-like magnetization distributions consisting of vortex and half-antivortex pairs, with nearly in-plane-magnetized cores, occurs. The size of vortex core size, along the direction perpendicular to the layer plane, could be tuned by changing either the N or the thickness of the nonferromagnetic spacer. The experimental observations confirm qualitatively the results of micromagnetic simulation. Large (of micrometer size) metastable domains with in-plane-oriented magnetization, associated with the core vortex, modulated by small domains (of submicrometer size) with perpendicular component of magnetization and sizes defined mainly by magnetostatics, were observed experimentally.

It was shown that the increase of N leads to the following effects: changes of shape of the hysteresis loop, substantial increase of the saturation field, and changes of both geometry and size of domain structure. In multilayers with $Q < 1$, the increase of N causes the nucleation of domains with out-of-plane component of magnetization in separate layers, which next induces interlayer magnetostatic interaction and, as a result, the phase transition to the states with perpendicular component of magnetization in the whole sample.

The researches of reversal processes in multilayer systems with $Q < 1$ and $Q > 1$ have shown that for small N the domain-like magnetization distributions are determined by the distribution of the coercivity field rather than by the existence of magnetostatics. However, when N increases, magnetostatic interaction becomes stronger, leading to the magnetization ordering, determined by magnetostatics.

Conclusion

In the series of publications the research results (obtained experimentally, by simulations and theoretically) of the magnetic properties in nanostructures have been reported. These nanostructures have been based on a cobalt layer with different number of repetition: from a single layer to multilayers. Many interesting results, concerning of magnetic ordering, domain structures and magnetization reversal processes, have been found. Many results have developed the fundamental knowledge of magnetism of low-dimension structures and would lead to a number of applications. The main results are following:

I – single magnetic layer systems

- demonstration of the possibility of both changes of Q -parameter and tuning of the perpendicular component of magnetization by nonferromagnetic both buffer and cover layers
- observation of different types of domain structures for various buffer layers and ferromagnetic layer thicknesses:
 - needle-like shape of domain structures in ultrathin cobalt films deposited on a Mo buffer layer; the explanation of the geometry in such structures by a strong magnetic anisotropy for Mo/Co systems with an in-plane-oriented easy magnetization axis,
 - dendritic-like domain structures in cobalt films with the value of the Q - parameter close to 1;
- observation of the drastic decrease of dimension of domain structure (about a few orders of magnitude) during decreasing the Q -parameter up to 1 and approaching the reorientation of magnetization from out-of-plane to in-plane direction
- elaboration of the procedure of remanence imaging using a polarizing magneto-optical microscopy, for studies of nanostructures with the perpendicular magnetic anisotropy

II – magnetic multilayer systems with $Q > 1$

- proving that an increase of the number of repetition, N , leads to a modification of magnetization reversal, namely to strong decrease of both coercivity and remanence magnetization and to transition from a hard magnet (with rectangular hysteresis shape) to a soft one
- observation of a strong decrease of domain structure size (to submicrometer size) while increasing the number of ferromagnetic layers

III – magnetic multilayer systems with $Q < 1$

- modification of the magnetic ordering induced by an increase number of repetition, N , from an in-plane magnetization to domain structures with perpendicular component of magnetization
- observation of the co-existence of two types of domain structures: (i) large, metastable magnetic domains, with the size in the range of micrometer and with the in-plane magnetization components, and (ii) smaller, submicron domains (modulating the mentioned above large domains) with perpendicular component of magnetization
- finding, by micromagnetic modelling, the spatial distribution of magnetization in each ferromagnetic layer for different Q and N ; by modification of such parameters one can obtain changes of magnetic ordering from an in-plane monodomain state to a vortex-like state with in-plane-oriented core; simulation results have been confirmed by experiment.

The knowledge of properties of artificial ultrathin structures is important from the point of view of application in nanotechnological area, especially in high-density magnetic-storage media, magnetoresistance heads of hard disk and new spintronic devices. The investigation of the static-magnetization-reversal process, which has been reported in the series of publication, is of the most importance for the explanation of fundamental mechanism in an ultrafast-dynamics-magnetization approach. One can expect, that in the future a new generation of combined-patterned-nanostructured multilayers of zero- and one-dimension systems (i.e. dots/pillars and wires) will lead to an observation of many new phenomena, which will occur on quantum level with a spatial manipulation of the spin.

2.5 Presentation of other scientific research achievements

In the year 1977 I started Master's studies at the Faculty of Mathematics and Natural Sciences, Warsaw University Branch in Bialystok, in physics, specializing in teaching. I performed the Master's thesis in the Laboratory of Physics of Magnetism, Warsaw University, Branch in Bialystok (currently Department of Physics of Magnetism, University of Bialystok) under the supervision of Prof. dr hab. Andrzej Maziewski. The Master Degree diploma entitled "*Magneto-optical analysis of magnetic after-effect in the garnet layer $Y_2Ca_1Fe_{3.9}Co_{0.1}Ge_1O_{12}$* " was finalized in December 1983.

In January 1984, I have started work in the Department of Physics, Warsaw University, Branch in Bialystok. Primarily, I was employed as a trainee in Computer Centre. In the subsequent years (1985 - September 1998) I worked in technical and scientific-technical jobs in the Laboratory of Physics of Magnetism (currently Department of Physics of Magnetism) which was headed conducted by Prof. dr hab. A. Maziewski. Since October 1998 I have been working as an assistant professor (adjunct).

Initially, I developed the technology, treatment of magnetic materials, and also the optical equipment in the Laboratory of Magnetism. In that time, I accomplished a few courses and trainings in this area, including a monthly Study of Phase and Interference Contrast Microscopy, organized by the Central Laboratory of Optics in Warsaw.

I was a co-author of creation, and, then, developing of a number of measurement systems, including a spatial polarizing microscopy systems for observation of both geometric and diffraction images of magnetic domain structures in a garnet films, using magneto-optical Faraday effect. I participated also in the creation of original software (in both Fortran and Pascal languages) for the analysis of the obtained images.

Thereafter, I took a very active part in the construction of digital image analysis system based on CCD cameras, and in the implementation of this system for the study of magnetic objects. I participated in the development of some new and original research methods based on techniques using magneto-optical both Faraday and Kerr effects.

2.5A. Achievements in scientific work before Ph.D.

From the beginning of my employment, I took an active part in the research and development works conducted at Laboratory and, then, at Department of Physics of Magnetism. The epitaxial films of cobalt-doped yttrium-iron garnets, additionally doped by different ions ((Lu, Bi, Co), deposited on the surface of gadolinium gallium garnet ($Gd_3Ga_5O_{12}$) was mainly of the object of study. The performed studies allowed observing a number of interesting effects, such as: a photomagnetic effect, a domain structure shape memory effect, a self biasing effect or, yet, disaccommodation of magnetic susceptibility. The experimental facts indicated that the observed phenomena were determined by temperature changes of anisotropy energy, induced in the growth process. Therefore, I got involved in profound and systematic researches, magnetic anisotropy of garnet films containing strongly

anisotropic cobalt ions, performed in a wide temperature range. This topic became the main goal of the doctoral dissertation. The research was performed in international collaboration with physicists from Ukraine, Russia, Germany and France. In the years 1994-1996 I had a research internship at the Institute for Physical High Technology in Jena and University of Leipzig in order to make measurements of the anisotropy using a both torque and SQUID methods.

My doctor degree procedure was started in December, 1994. I received a State Committee for Scientific Research (KBN) grant in order to conduct further research related to the doctor's thesis. The effects of the research have been presented in the dissertation entitled "*Magnetic anisotropy and phase transitions connected with magnetization reorientation in the cobalt doped garnet films*", prepared under the supervision of prof. dr hab. Andrzej Maziewski. The defense was held at Institute of Physics, Polish Academy of Sciences in Warsaw in April, 1998.

2.5B. Achievements in research work after Ph.D.

After obtaining the degree of doctor, my scientific activities were concerned on the magnetic nanostructures, mainly on ultrathin cobalt layers. Nanomagnetism is one of the most intensively developed of research areas in the Department of Physics of Magnetism. Originally, the all my work was focused on the visualization of the magnetic domain structures in Au/Co/Au systems, produced in the Institute of Physics, Polish Academy of Science in Warsaw. In these systems, one has observed a perpendicular magnetic anisotropy and the presence of a reorientation of magnetization from the out-of-plane state to the in-plane one, with increasing thickness of cobalt in atomic monolayers [*Physical Review Letters* 89, 8, 87203 (2002)]. New systems of layers, in the shape of a double wedge of both a ferromagnetic layer and a buffer layer became especially intriguing. Magneto-optical techniques, which have been used for many years in the Department of Physics of Magnetism, proved to be extremely useful for investigation of these systems due to the local studies with large spatial resolution. A method of remanence imaging, which was suggested and developed by me in the system of polarizing optical microscopy, became an important supplement of classical measurements of the magnetization curves by magneto-optical Kerr technique. The main advantage of this method was a quick registration (with the accumulation time of about 1 second) of the whole image of the sample (with typical dimensions of $(10 \times 10) \text{ mm}^2$) with a magneto-optical Kerr microscopy technique in the polar configuration. The image contrast, obtained from the differential analysis, was correspond to the Kerr rotation, and finally to the perpendicular component of magnetization. In the case of a sample composed with a many areas of different layer composition and/or of different thickness, this method allows to observe magnetic maps, areas with different coercivity as a function of the external magnetic field, submillimeter domain structures, and gradient domain walls.

The study was performed in collaboration with research centres in France, Czech Republic, Ukraine and Poland within the Polish KBN grant and NANOMAG program of the European Science Foundation (ESF). One obtained a number of interesting results concerning the magnetization processes of cobalt layers deposited on mica and sapphire substrates. The most important results were the following: (i) the observation of phase transitions connected with the reorientation of easy magnetization axis: the easy axis - easy plane, (ii) the observation of changes in the nature of the domain structure induced by cobalt thickness, (iii) quantitative analysis of the drastic changes in the size and type of domain structure (including the determination of the number of nucleation centres and fractal dimension) as a result of the change of the thickness of the magnetic layer, (iv) investigation of the influence of covering layer structure on the localization of the coercivity wall and the properties of the domain structures.

During my long-lasting collaboration with the Leibniz-Institut für Festkörper- und Werkstoffforschung IWF in Dresden, I dealt with a modification of the magneto-optical microscope for visualization of magnetic domain structures with in-plane oriented magnetization. The result of this cooperation, within NANOMAG-LAB project, was the successful launch of a new microscopic system based on specialized diaphragms, which modify the observation area in the conoscopic image. This approach gave the opportunity to observe the magnetic structures having both perpendicular and in-plane oriented components of magnetization, in accordance with the geometry of basic Kerr configurations (polar, longitudinal, and transversal) of very high imaging spatial resolution (up to 400nm).

Next researches, conducted with my active participation, were centred on the influence of the surrounding layers (cover and/or buffer layers) on the magnetic properties and magnetization processes in a single ultrathin layers (e.g. cobalt and iron). These studies were carried out as a function of such parameters of the surrounding layers, as thickness, morphology and chemical composition (Au, Ag, Mo, V, Cr, Pt). The main results concerned: the modification of the cobalt layer coercivity by changing both the geometry and the kind of the surrounding layers, in a wide range of their thicknesses, spatial modelling of domain structures induced by the thickness of magnetic, cover, and buffer layers, the drastic changes of the size of the magnetic domain structure (a few orders of magnitude in the spin reorientation range).

The understanding of the mechanisms of the magnetization evolution for single layers in a micrometer scale, was an inspiration to produce, in collaboration with the Institute of Molecular Physics, Polish Academy of Sciences in Poznań, some other intriguing configurations of nanostructures with variable multiplicity of the magnetic layer (Ni₈₀Fe₂₀/Au/Co/Au)_N, showing a giant magnetoresistance effect. I was involved in the study of magnetic properties of these materials in an active manner. I performed the observation and analysis of domain structures and magnetization processes within a wide range of magnetic layer thickness and changeable multiplicity, with the use of magneto-optical techniques. Particularly interesting results were obtained for magnetostatically coupled systems. I participated also in the gradient-domain-walls analysis and their changes under the influence of ion bombardment [*Physical Review Letters* 105, 067202 (2010)].

Additionally, I participated in the studies of magnetic anisotropy and magnetization processes in Pt/Co/Pt layers. In particular, the project of homogeneous irradiation of a thin magnetic Pt/Co/Pt film by Ga⁺ ions, was noteworthy [*Applied Physics Letters* 95, 022502 (2009)]. This project was carried out in collaboration with the Laboratoire de Physique des Solides, University Paris-Sud, Orsay Cedex and Ion Beam Physics and Material Research, Forschungszentrum Dresden-Rossendorf, Dresden. The studies have shown that, in a cobalt layer with the in-plane-oriented magnetization, as a result of Ga⁺ ions implantation, the reorientation of magnetization to the perpendicular direction is going on.

In the recent years, I participated in the studies of magnetization ordering in ultrathin cobalt films deposited on vicinal surfaces. I was involved also in the studies of magnetization processes in permalloy nanowires and amorphous cobalt microwires with circular domain structure, by using of the high resolution magneto-optical microscopy with detection of the planar component of magnetization.

In the recent time, I was dealing with the visualization and analysis of the magnetic domain structures images in spatially structured thin garnet films (Co/YIG/Py/YIG). The interesting photomagnetic effects and spin-waves excitation are observed in this material.

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