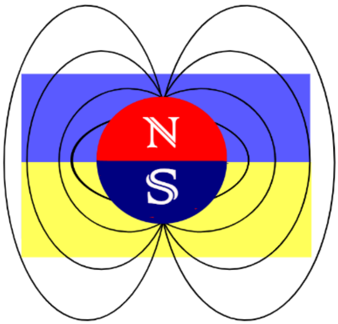
Institute of Magnetism of the NAS of Ukraine and MES of Ukraine
Science & Technology Center in Ukraine

IEEE Magnetics Society

Workshop Program
&
Book of Abstracts



IEEE Magnetics Society "Magnetism for Ukraine Initiative" Workshop

14 November, 2024
Kyiv, Ukraine

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Organizer

Institute of Magnetism of the NAS of Ukraine and MES of Ukraine

Under support of

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IEEE Magnetics Society

The Vision of the IEEE Magnetics Society (https://ieeemagnetics.org/) is to be the leading international professional organization for magnetism and for related professionals throughout the world.

Mission: The IEEE Magnetics Society promotes the advancement of science, technology, applications and training in magnetism. It fosters presentation and exchange of information among its members and within the global technical community, including education and training of young engineers and scientists. It seeks to nurture positive interactions between all national and regional societies acting in the field of magnetism. The Society maintains the highest standard of professionalism and technical competency.

The IEEE Magnetics Society shall be involved with the:

"Treatment of all matters in which the dominant factors are the fundamental developments, design, and certain applications of magnetic devices. This includes consideration of materials and components as used therein, standardization of definitions, nomenclature, symbols, and operating characteristics; and exchange of information as by technical papers, conference sessions, and demonstrations."

As excerpted from the IEEE Magnetic Society's Constitution, the efforts of the IEEE Magnetics Society "shall be scientific, literary, and educational in character. The IEEE Magnetics Society shall strive for the advancement of the theory and practice of electrical and electronics engineering and of the allied arts and sciences, and the maintenance of a high professional standing among its members, all in consonance with the Constitution and Bylaws of the IEEE and with special attention to such aims within the field of interest of the Society as are hereinafter defined. The Society shall aid in promoting close cooperation and exchange of technical information among its members and to this end shall hold meetings for the presentation of papers and their discussion, and through its committees shall study and provide for the needs of its members."

Science & Technology Center in Ukraine

The STCU (http://www.stcu.int/) Vision Statement:

To advance global peace and prosperity through cooperative Chemical, Biological, Radiological, and Nuclear (CBRN) risk mitigation by supporting civilian science and technology partnerships and collaborations that address global security threats and advance non-proliferation.

STCU Mission:

- To address the global security threat of the proliferation of weapon of mass destruction (WMD)-applicable chemical, biological, radiological and nuclear knowledge and materials;
- To support the integration of scientists with WMD applicable knowledge into global scientific and economic communities through national, regional, and international research collaboration;
- To develop and sustain a culture of nonproliferation and CBRN security awareness and responsibility through education, mentorship, and training;
- To promote international best practices and security culture to mitigate CBRN security threats.

Near-Term Strategy:

The STCU has to take the lead in helping the scientists and institutes stand on their own by guiding them towards successful integration into the global economic and business communities. The goal is for STCU grant recipients to become self-sustaining and to make high-value contributions to domestic and global science and technology issues (both commercial and non-commercial). They must be weaned from dependence on the donor Parties' STCU project funding and be given the skills, experience, and reputation to compete and contribute on their own in the international science, academic, and commercial worlds.

IEEE Magnetics Society “Magnetism for Ukraine” Initiative 2022-2024

Objectives of the program and its organization

The Magnetics Society assisted in the support and recovery of science and technology in Ukraine by creating a new program with the goal of promoting ongoing R&D and a strong professional community in Magnetics.

This goal was accomplished by providing small grants to support the research and professional development for scientists, engineers and students working in magnetics and members of the Magnetics Society, with a preference for grants that will impact small groups of researchers and connect the broader community.

In this program, the IEEE MagSoc worked with a respected partner to help manage the proposal collection, evaluation, subcontracting, reporting, and financial accounting. The program was launched under the leadership of IEEE MagSoc with the support provided by the Science and Technology Center in Ukraine (STCU, http://www.stcu.int/) and Institute of Magnetism of the NAS of Ukraine and MES of Ukraine (http://eng.imag.kiev.ua).

Execution of the program

The STCU has received 116 excellent applications and via a competitive selection identified 37 research projects that have been funded in 2022-2024. The reviewing was performed by the team of 43 active researchers including the representatives of IEEE MagSoc Technical Committee and was based on the standard criteria of idea, novelty, track records of the researchers, diversity and international collaboration. 113 magnetics researchers have received financial support, including 31 women and 17 students. The researchers receiving support are from Kyiv, Kharkiv, Sumy, Donetsk, Drohobych, Lviv and Dnipro.

In terms of publications, 44 peer-reviewed publications and one book chapter have been published with acknowledgement to the IEEE MagSoc "Magnetism for Ukraine" program (20 of them in Q1-Q2 journals). Many of the scientific achievements have been or will be presented at international conferences (more than 30 conference abstracts have been published so far, among them – 3 invited).The research carried out within the Program has contributed to a successful defense of 3 PhD.

The successful applicants were encouraged to become IEEE MagSoc members to strengthen the international integration of Ukrainian research. In total, 84 new members have joined IEEE MagSoc.

IEEE Magnetics “Magnetism for Ukraine Initiative” Workshop

Workshop program

November 14, 2024

Institute of Magnetism, 36-b Acad. Vernadskogo Blvd, Kyiv, Ukraine

http://ukr.imag.kiev.ua/ http://eng.imag.kiev.ua/

9-00 Opening ceremony

9-15 Welcome words

10-00 Presentations

11:30 Coffee break

11-45 Presentations

13:00 Lunch break

14-00 Presentations

15:30 Coffee break

15-45 Presentations

18-00 Closing ceremony

IEEE Magnetics "Magnetism for Ukraine Initiative" Workshop

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INFLUENCE OF NON-EQUILIBRIUM ON CRITICAL BENDING OF MAGNETOACTIVE ELASTOMERS

S. M. Ryabchenko[1], A. V. Bodnaruk[1], Yu. I. Dzhezherya[2], S. V. Cherepov[2], Yu. B. Skirta[2], V. M. Kalita[3]

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Magnetoactive elastomers (MAE) belong to the class of “smart” materials. MAEs are composites consisting of an elastomer matrix with embedded magnetic filler particles. MAEs are easily affected by external magnetic field **H**. For $H \neq 0$ a restructuring effect occurs - a change in the mutual arrangement of particles in the MAE matrix. MAEs have an anomalous magnetorheological effect, shape memory effect, large magnetodielectric effect and magnetostriction. MAEs advanced materials for soft robots, origami, actuators, metamaterials.

In the homogeneous transverse magnetic field **H** in the MAE, the effect of critical bending is observed. At $H<H_{cr}$ Fig. 1 (a) the beam is not bent, its magnetization **m** || **H**. This is a highly symmetrical state [1], the beam does not change the symmetry of its shape, **m** is directed along the axis of symmetry of the beam, the beam energy *W* has one minimum (Fig. 1 (e)) [1].

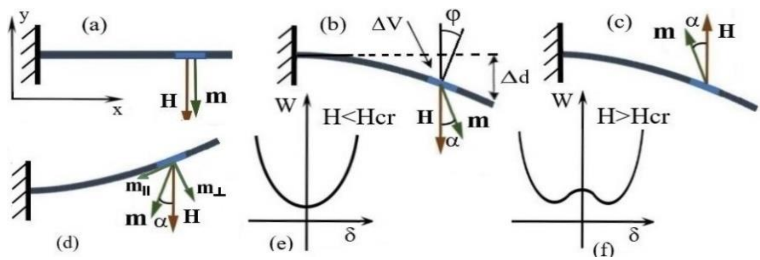

Fig. 1. (a)-(d) states of the MAE beam in a transverse uniform field. (e), (f) graphs of total energy *W* from the value of relative bending δ for $H<H_{cr}$ and $H>H_{cr}$.

At $H>H_{cr}$ the beam bends (Fig. 1 (a) - (d)) and goes into a low-symmetric state – the shape of the beam changes, m deviates from the axis of symmetry, the energy *W* has two symmetric minima [1]. For $H=H_{cr}$, a magnetic orientational phase transition occurs in MAE [1]. The critical bending and the magnetic phase transition are interrelated: near the threshold field at $H>H_{cr}$ the bending value, $\delta=\Delta d/l$, where l – where l is the length of the beam, is directly proportional to the average projection of the magnetization $m_{||}$ (Fig. 1(d)) [1]. For $H=H_{cr}$, bending occurs spontaneously and with equal probability, along or opposite to the magnetic field.

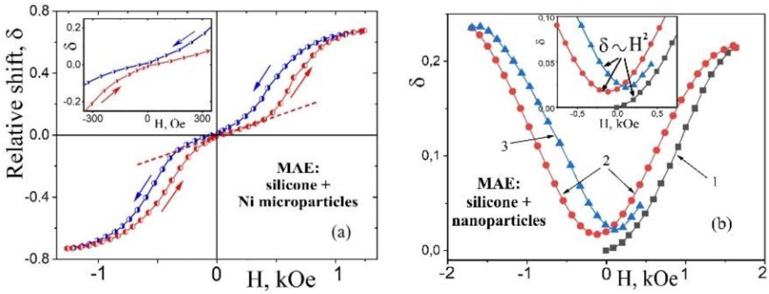

Fig. 2. Field dependencies for the magnitude of bending $\delta(H)$ [1,2]

Fig. 2 shows the experimental graphs for the field dependence of bending $\delta(H)$ [1, 2]. The restructuring effect leads to non-equilibrium in the bending hysteresis and to a shift in the positions of critical points [1]. In Fig. 2(a), the bending changes direction when the sign of the field changes, the uncertainty of the bending direction is eliminated due to the remanence of Ni microparticles [1]. For MAE with nanoparticles $La_{0.6}Ag_{0.2}Mn_{1.2}O_3$ in Fig. 2 bending value δ does not change sign when $H\rightarrow-H$. This is a consequence of the influence of non-equilibrium due to plastic deformation [2] after the first introduction of the field (curve 1 and 2).

The work was supported by the IEEE "Magnetism for Ukraine 2022/2023 initiative" (STCU project #9918), project entitled "The influence of the restructuring effect on the magnetic and magnetoelastic properties of magnetoactive elastomers".

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[1] V. M. Kalita *et al.*, Spontaneous change of symmetry in a magnetoactive elastomer beam at its critical bending induced by a magnetic field, Smart Mater. Struct. **32**, 045002 (2023).

[2] V. M. Kalita *et al.*, Influence of plasticity on the magnetic-field-induced bending deformation in a magneto-active elastomer with superparamagnetic nanoparticles, AIP Advances **14**, 015143 (2024).

TEMPERATURE EFFECTS ON MAGNETIC ANISOTROPY AND DOMAIN WALL PARAMETERS IN Al-DOPED YTTRIUM IRON GARNETS

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Since the middle of the 20th century, yttrium-iron garnets (YIG) have gained great recognition in various fields of technology, especially in microwave electronics, due to their superior electrical and magnetic properties [1]. However, depending on the operating regime of a final device, additional requirements may be placed on the magnetic material of choice. In this context, the complex crystal structure of YIG provides a reliable way to achieve the desired functional properties. Thus, an increasing interest in substituted garnets with different dopants (Sm, In, La, Co, Ni, Mn, etc.) has been observed in recent years.

In the present work, we investigate the temperature-induced changes in the magnetic parameters of Al-doped yttrium-iron garnet ceramics $Y_3AlFe_4O_{12}$ (YAIG), prepared using our newly proposed efficient route for co-precipitation in aqueous solution [2]. Magnetostatic measurements were performed in the temperature range of 3-370 K using a PPMS DynaCool (Quantum Design Inc.) equipped with a VSM magnetometer.

Experimental hysteresis loops revealed soft magnetic behavior of YAIG ceramic samples and allowed us to determine its key magnetic parameters, coercive force H_c (panel (a) in Fig. 1) and saturation magnetization M_s (panel (b)). The highest coercive force reached at 3 K was 55 Oe, which is significantly higher than that of a pure YIG (~40 Oe). However, the room-temperature coercivity values were rather low, $\lesssim$ 5 Oe. The polycrystalline nature of YAIG ceramics obscures the origin for the observed coercive behavior, as a number of intrinsic physical properties are involved in the magnetization process of the bulk sample, *e.g.* domain wall motion, demagnetization, structural and magnetic inhomogeneities.

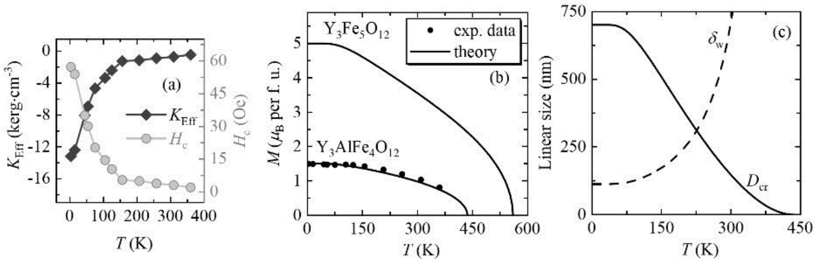

Fig. 1. (a) Temperature dependencies of the K_{eff} constant and coercivity H_c. (b) Comparison of the experimental and calculated thermomagnetization curves. (c) Temperature dependencies of critical single-domain size D_{cr} and domain wall width δ_w for YAIG.

We used the law of approach to saturation [3] to fit the high-field part of the hysteresis loops and separate the effective magnetic anisotropy constant, K_{eff}, from other contributions. Remarkably, both the coercivity H_c and the extracted K_{eff} constant show similar exponential-like trend in temperature variation (see panel (a)). Using the Brillouin-Weiss model, adapted for substituted garnets [3], the temperature dependence of the saturation magnetization was calculated for YAIG (panel (b)). The theoretical thermomagnetization curve well reproduces both the gradual fall-off observed in experimental data, and the expected drop in low-temperature saturation magnetization as compared to pure YIG, originated from predominant Al^{3+} substitution in tetrahedral Fe-sublattice.

The knowledge of both K_{eff} and M_s made it possible to estimate the characteristic domain structure parameters for YAIG ceramics (panel (c)). Our findings provide necessary insights for further optimization of a garnet material composition to meet the needs of current technological demands.

This work was partially supported by the IEEE “Magnetism for Ukraine initiative” (STCU project #9918) and NAS of Ukraine (grants #0124U002212 in the framework of the Target Program “Grants of the NAS of Ukraine to research laboratories/groups of young scientists of the NAS of Ukraine”, 2024–2025).

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[1] V. Harris, *Modern Ferrites: Emerging Technologies and Applications*, Wiley, 2022.

[2] S. Solopan et al., Nanoscale $Y_3AlFe_4O_{12}$ Garnets: Looking into Subtle Features of Crystalline Structure and Properties Formation, J. Alloys Compd. **968**, 172248 (2023).

[3] G. F. Dionne, Determination of Magnetic Anisotropy and Porosity from the Approach to Saturation of Polycrystalline Ferrites, J. Appl. Phys. **40**, 1839 (1969).

MAGNETIC RESONANCE STUDY OF IMPURITIES AND INCLUSIONS IN SYNTHETIC DIAMONDS

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In order to achieve diamond synthesis in the laboratory, high pressure and high temperature (HPHT) conditions are needed. In addition to them, the production of synthetic diamond requires the introduction of ferromagnetic solvent-catalysts into the reaction mixture, as a result of which relatively large amounts of metal remain as impurities and agglomerates into nanoclusters and microinclusions in the finished product. For this reason, the overwhelming majority of synthetic diamonds are ferromagnetic. This presentation is focused on the electron paramagnetic resonance (EPR) and ferromagnetic resonance (FMR) traits of domestic HPHT-diamonds.

Diamond single crystals were mainly grown in solution-melt systems based on Fe-Co doped with Ti, Zr and Mg or Fe-Ni catalysts. This makes it possible to obtain type Ib, IIa and IIb diamonds of 5–15 carats in size with a controlled defect-impurity composition. Magnetic resonance (MR) study was carried out in the temperature range of 100–300K and the field range of 0–7000 G using X-band EPR spectrometers operating at 9.44 GHz.

Multifarious magnetic resonance spectra have been registered depending on type of metal catalysts and dopants. Typical MR spectra for different types of HPHT-diamond are shown in Fig. 1. In the general case, there is a distinct wide line in low magnetic field and several less intense lines in higher field. Preliminarily, the low-field part was attributed to lines of superparamagnetic resonance while other lines were assigned to FMR. To elucidate their origin, the angular and temperature dependences were experimentally examined in detail. As a rule, the experimental spectra were simulated by a set of Lorentzian functions to find the angular dependence of the resonance fields for each signal and sample. A giant shift of one FMR spectrum to lower magnetic field with temperature increase was revealed. It was attributed to Villari effect owing to considerable distinctions between thermal expansion coefficients for diamond and metal inclusions.

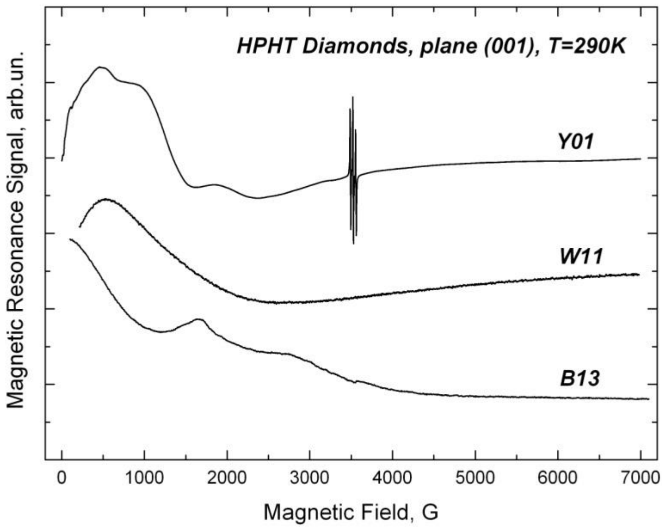

Fig. 1. Magnetic resonance spectra of synthetic diamonds: yellow with brown tint undoped crystal *Y01* (type Ib), moderately boron-doped colorless white *W11* (type IIa) and intensively boron-doped blue-gray crystal *B13* (type IIb). Narrow lines of the sample *Y01* in the range of 3550 G belong to the EPR spectrum of the nitrogen impurity.

For Ib diamonds, a comparison of the position and width of the EPR lines in the spectra of N-impurity for HPHT crystals with a low and high concentration of FM inclusions makes it possible to determine their influence on local magnetic fields.

The theoretical analysis and simulation of experimental spectra made it possible to determine magnetic characteristics of the FM inclusions in all the samples studied. In addition, the shape of magnetic particles was estimated and it was established that they have mainly cubic-like shape.

The work was supported by the IEEE "Magnetism for Ukraine 2022/2023 initiative" (STCU project #9918), project entitled "Magnetic resonance spectroscopy of the HPHT synthetic diamond".

ELECTROMAGNETIC WAVES AT THE INTERFACE BETWEEN VACUUM AND LOSSY METAMATERIAL WITH ZERO REAL PART OF PERMITTIVITY

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We present a theoretical investigation of the electromagnetic waves refraction and reflection at the interface between vacuum and lossy metamaterial with zero real part of permittivity ε. The calculation results are given for the complex permittivity and permeability $\varepsilon = i\varepsilon'', \mu = 1 + i\mu''$. It is shown for the interface of the lossy epsilon-near-zero (ENZ) medium that even for the very small losses the value of the reflection coefficient *R* can be far from 1 over a wide range of the incidence angles, for any wave polarization. We demonstrate that at the interface of the lossy ENZ medium the significant transmission can exist at any angles of incidence θ_i and show that the polarization of the incident wave essentially affects the optical properties of the interface of the ENZ medium.

We find that for s and p-polarized waves the transmission coefficient *T*

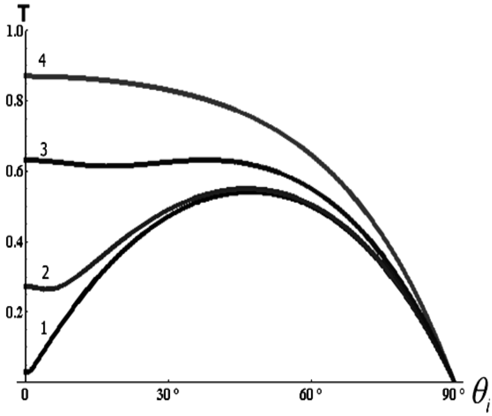

Fig. 1**.** The transmission coefficient $\boldsymbol{T}$ as function of the angle of incidence $\boldsymbol{\theta_i}$ for s-polarized wave, at $\boldsymbol{\mu'' = 0.4}$ for different values of $\boldsymbol{\varepsilon''}$**:**
$\mathbf{1.\ \varepsilon'' = 0.001}$; $\mathbf{2.\ \varepsilon'' = 0.01}$; $\mathbf{3.\ \varepsilon'' = 0.1}$; $\mathbf{4.\ \varepsilon'' = 0.5}$.

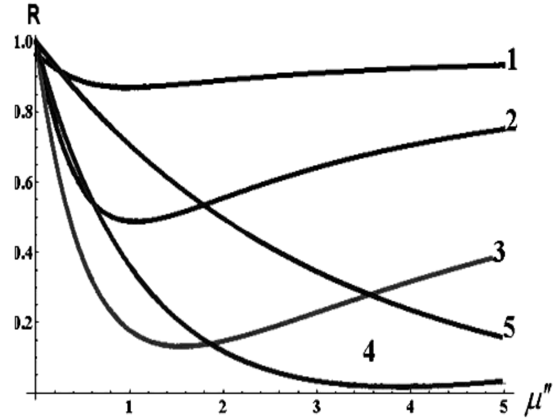

Fig. 2. The reflection coefficient R as function of μ'', at $\varepsilon'' = 0.001$ for s-polarized wave**,** for different values of angles of incidence θ_i:

1. $\theta_i = 3°$; 2. $\theta_i = 20°$; 3. $\theta_i = 50°$; 4. $\theta_i = 75°$; 5. $\theta_i = 85°$.

increases with increasing the value of ε'' (Fig.1), but only for s-polarized wave T significant increases with increasing the value of μ''. For s-polarized wave, the difference between the angle of refraction θ_t and the transmission angle of Poynting vector ψ is mainly determined by the value of μ''. In contrast to article [1], we took into account the absorption of the wave and obtained overall correct picture of refraction of wave at an interface of ENZ metamaterial.

The work was supported by the IEEE "Magnetism for Ukraine 2022/2023 initiative" (STCU project #9918), project entitled "Features of transmission and reflection of electromagnetic waves at an interface between vacuum and lossy metamaterial with zero real part of permittivity".

References:

[1] Z. Xu and H. F Arnoldus, Reflection by and transmission through an ENZ interface, OSA Continuum **2**, 722 (2019).

OPTICAL PROPERTIES OF MAGNETIC–«EPSILON-NEAR-ZERO» MULTILAYERS WITH NONCOLLINEAR ORIENTATION OF MAGNETIZATIONS

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The transmission of electromagnetic waves through the magnetic-«epsilon-near-zero» multilayer with a noncollinear orientation of the magnetizations of layers, lying in the plane of the film, is analytically described by macroscopic classical electrodynamics. The results were obtained for structure composed of several magnetic layers and nonmagnetic interlayers, one of which is ENZ material, in which permittivity ε≈0. We explored the transmission of linearly polarized electromagnetic waves through that structure. Both the magnitude and the character of the obtained dependences are analyzed in relation to the angles Ω and γ between the magnetizations, the angle of incidence ϕ and to the polarization of the incident wave. The presence ENZ interlayer in the multilayer leads to a dramatic difference in how this structure interacts with p- and s-polarized electromagnetic waves.

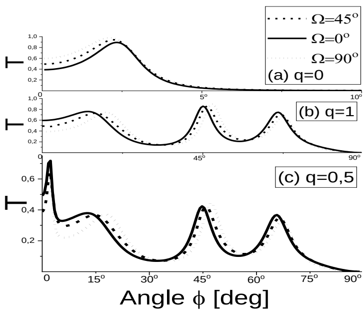

Fig. 1. The transmission coefficient as a function of the angle of incidence ϕ for the different values of the angle Ω between the magnetizations (0° - solid curve, 90° - dotted curve, 45° - dashed curve) and various polarization of incident wave: a) (q=0) p-polarization, b) (q=1) s-polarization, c) (q=0.5) mixed polarization ($q = \frac{\left|E_s^{(0)}\right|^2}{\left|E_+^{(0)}\right|^2}$=1, where $\left|E_+^{(0)}\right|^2 = \left|E_{s+}^{(0)}\right|^2 + \left|E_{p+}^{(0)}\right|^2$).

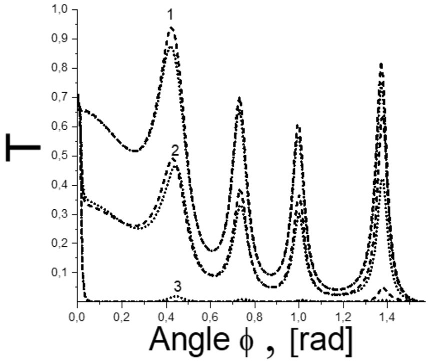

Fig. 2. Dependences of the transmission coefficient *T* on the angle of incidence ϕ for the various polarization of the incident wave and for the different values of the angles Ω and γ between the magnetizations:1.(q=1) Ω=45^o, γ=60 ^{o}; 2. (q=0.5) Ω=45^o, γ=90 ^{o}; 3. (q=0) Ω=45^o, γ=90 ^{o} (dashed curves correspond to forward waves, dotted curves correspond to reverse waves).

The results presented for oblique incidence demonstrate a strong dependence of the optical characteristics on the angles Ω and γ between the magnetizations in the layers. Our results suggest availability electromagnetic wave transmission at and above the critical angle for multilayer with ENZ interlayer. It was shown that the non-reciprocal properties of the waves strong show themselves (Fig.2). Our results show the dramatic influence that parameters of the magnetic-«epsilon-near-zero» multilayer, in particular angles between the magnetizations, has especially on the reflection and transmission of s-polarized waves. The transmission of the p-polarized waves, in contrast, depends less on parameters, but at the same time demonstrates the unique properties inherent in the ENZ medium. Thus, magnetic-«epsilon-near-zero» multilayer has unique properties of highly selective angular filter and polarizer.

The work was supported by the IEEE “Magnetism for Ukraine 2022/2023 initiative” (STCU project #9918), project entitled “Electromagnetic properties of a magnetic-«epsilon-near-zero» superlattice, with noncollinear orientation of magnetizations, controlled by an external magnetic field: nonreciprocity, total reflection or transmission, surface waves”

MAGNETIC PROPERTIES OF MODEL NANOMAGNETS WITH MACROSCOPIC VALUE OF GROUND STATE SPIN ON THE BASE OF POLYMERIC COMPLEXES OF TRANSITION METALS

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Our project is devoted to the analytical and numerical study of the peculiarities of the energy spectra and magnetic properties of the spin models of quasi-one-dimensional polymeric complexes of transition metals. The main attention was given to the mixed spin systems which in the case of isotropic antiferromagnetic Heisenberg spin coupling have macroscopic value of the ground state spin. In particular, we considered two these systems. The first one is a set of 3-spin ½ chain fragments connected by additional site spins S into the "bunch" via intermediate spin ½ for each 3-spin chain fragment. The second system is formed by the same 3-spin fragments connected by two additional spins S via the spins located at the ends of each fragment [1, 2]. For antiferromagnetic spin coupling the above systems should have macroscopic value of the ground state spin according to Lieb theorem.

In case of Ising interactions with additional spins S, the energy spectra and thermodynamics of the both spin models can be treated in details even in the presence of external magnetic field and different g-factors for fragment spins and additional Ising spins. The simple block character of the corresponding anisotropic spin Hamiltonians permits us to use standard transfer-matrix technique for numerical simulation of the thermodynamics for both models. For simplicity, we restricted our consideration by the Ising spins S=1/2. For both models the field dependence of magnetization at low temperatures demonstrates the possibility of the appearance of intermediate magnetization plateaus. We also determine the appearance of zero values for pair correlation function $< S_i^z S_{i+1}^z >$ for neighbor Ising spins at some critical values of external magnetic field and low temperatures. We presented simple analytical explanation of this effect due to the appearance of partial degeneracy of the corresponding energy levels of our models.

In addition, we studied the isotropic Heisenberg mixed spin system formed by three-spin unit cells, which can be considered as the two-leg spin 1/2 ladder model with additional spins $s \geq 1/2$ inside the ladder rungs (decorated spin ladder model). It is of interest, that our consideration on the base of perturbation theory and the density-matrix renormalization group (DMRG) demonstrates the existence of intermediate plateau in low-temperature magnetization profile despite the singlet ground state of this spin ladder model. [3]. We found, that the Ising type of interactions in ladder rungs may leads to the disappearance of the above intermediate magnetization plateau for the corresponding isotropic spin ladder.

We investigated also the relationship between energy spectrum of finite clusters of *S*=1 Heisenberg antiferromagnets with homogeneous single-ion anisotropy and their lattice structure using perturbation theory and linear spin wave approximation. In particular, our study explains the remarkable similarity of the energy spectra in subspace with the magnetization *M*=0 for *S*=1 antiferromagnetic Heisenberg model with single-ion anisotropy on bipartite cospectral regular graphs [4].

The results of above study will be useful for targeted design of the new magnetic materials on the base of transition metal complexes.

The work was supported by the IEEE "Magnetism for Ukraine 2022/2023 initiative" (STCU project #9918), project entitled "Magnetic properties of model nanomagnets with macroscopic value of ground state spin on the base of polymeric complexes of the transition metals".

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PIEZOMAGNETISM of $FeSe_{1-x}S_x$ SUPERCONDUCTOR in the MIXED STATE

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The acoustoelectric transformation (AET) experiments on FeSe and $FeSe_{1-x}S_x$ [1,2] demonstrated features that should be accounted for the presence of piezomagnetic interaction in these compounds.

The essence of the AET experiment is the following. The sample under study is excited by a transverse sound wave. The sound wave induces electromagnetic field oscillations radiated from a free surface of the sample in a form of a plane wave. A loop antenna registers the amplitude and the phase of the radiated wave. This information allows determining the mechanism of AET in a given compound.

In zero magnetic field, in the absence of magnetoelastic interaction the mechanism of AET is the acoustic Stewart–Tolman effect [3]. Piezomagnetic interaction may cause a much larger AET response. The power of the AET method in registering piezomagnetism was demonstrated in [4,5] with reference to known piezomagnetic compounds, CoF_2 and MnF_2.

In [6], we investigated the AET response of $FeSe_{1-x}S_x$ superconductor. Theoretical analysis showed that the AET response associated with the piezomagnetism should decrease sharply under the transition from the normal to the superconducting state. This prediction is in agreement with the experimental result, Fig. 1. In the magnetic field B applied to the sample perpendicular to the radiating surface, an increase of the AET response was observed in the mixed state. It was found that the amplitude of the even in B part of the signal changes linearly with the magnetic field. The mechanism responsible for this unexpected feature was clarified. The piezomagnetic contribution to the AET response of FeSe in superconducting state is proportional to the square of the London penetration depth λ_L. A motion of Abrikosov vortexes results in a renormalization of λ_L. The dynamics of vortexes is governed by the viscous friction force with the viscosity coefficient η proportional to $|B|$. In a wide range of B the square of the renormalized λ_L is proportional to η, that determines the observed magnetic field dependence of the AET signal. The experiment [6] confirmed the piezomagnetic origin of the AET response in $FeSe_{1-x}S_x$. The piezomagnetic modulus can be evaluated from the slope of the dependence of the even part of the AET signal on *B*.

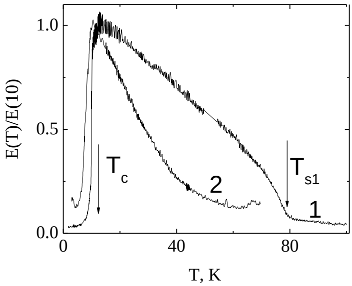

Fig. 1. Temperature dependence of the amplitude of the radiation field in $FeSe_{1-x}S_x$. with x = 0.075 (curve 1) and x = 0.18 (curve 2). T_{s1} is the temperature of the structural phase transition in the sample 1, T_c is the superconducting transition temperature.

Piezomagnetism of $FeSe_{1-x}S_x$ implies the existence of a hidden magnetic order with the order parameter odd with respect to spin variables.

The authors acknowledge the financial support by the IEEE "Magnetism for Ukraine 2022/2023 initiative" (STCU project #9918), project entitled "Piezomagnetism and hidden magnetic order in FeSe based superconductors".

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THE FEATURES OF MAGNETOSENSITIVITY OF *Photobacterium phosphoreum*

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Introduction. Currently, research is being conducted to identify the mechanisms that enable living organisms to sense and utilize the Earth's magnetic field for orientation and navigation. The primary hypothetical mechanisms under active discussion include the radical pair model, which involves magnetosensitive free radical redox reactions in enzymatic systems containing oxygen molecules and flavin compounds (such as cryptochromes and bacterial luciferases), as well as the model involving intracellular magnetic magnetite particles interacting with the magnetic field. Our focus is on the first hypothesis. Therefore, the aim of our study was to investigate the effects of constant and extremely low frequency magnetic fields on the bioluminescence of *Photobacterium phosphoreum*, based on a flavin oxidation reaction. Notably, photobacteria are widely used as bioindicators of water pollution and indicators of exposure to various biologically active compounds.

Methods. We measured the bioluminescence of *P. phosphoreum* in liquid media of standard composition for bacterial nutrient medium at room temperature (22-24°C). The baseline bioluminescence was evaluated over several days following inoculation in the culture medium. Bioluminescence was recorded using digital photoregistration, with subsequent image processing conducted in ImageJ or OriginPro. Magnetic field exposure was applied in two modes. In the first mode, bacterial suspensions were exposed to the magnetic field continuously from the moment of inoculation throughout the entire growth period. In the second mode, short-term magnetic field exposure was applied for several minutes after active hydrodynamic stirring of the bacterial suspension, which triggered a burst of luminescence, followed by fading and a return to the baseline level. This procedure for activating bioluminescence is described in [1]. The magnetic field induction was measured using a Hall sensor.

Results. Relatively strong static magnetic fields in the range of 2-8 mT weakly activated bioluminescence during the active growth phase of the bacterial population, but they statistically significantly suppressed the glow of bacteria during their maximum luminescence and subsequent dimming (Fig. 1A). The magnitude of the effects of the magnetic field was small, approximately 15% relative to the control values, but statistically significant.

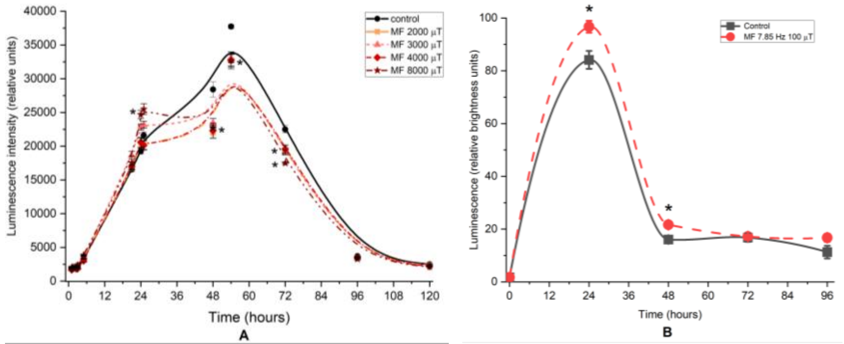

Fig.1. Effects of static (A) and extremely low frequency (B) magnetic field on basic luminescence of *P. phosphoreum.* The magnetic field was continuously applied during the entire period of observation of the development of the bacterial population in time (first mode). * - statistically significant P<0,05.

The influence of a low-frequency magnetic field with a frequency of 7.85 Hz and induction of 100 µT stimulated the baseline bioluminescence of the photobacteria (Fig. 1B). During short-term exposure to this extremely low frequency magnetic field, we observed a burst of luminescence initiated by the active hydrodynamic stirring of the bacterial suspension. This resulted in a significant increase in the intensity of baseline bioluminescence by 10-15%.

At the same time, the magnetic field did not significantly affect either the concentration of oxygen or the concentration of bacterial cells in suspension, indicating a direct influence of magnetic fields on the metabolic processes associated with the bioluminescent system of bacterial cells.

Conclusion. *P. phosphoreum* is sensitive to the action of static and extremely low-frequency fields, showing a biological efficiency within 15% of the control values. This bacterial model of magnetosensitivity is convenient for further experimental verification of the hypothesis regarding the magnetosensitivity of radical pairs.

The work was supported by the IEEE “Magnetism for Ukraine 2022/2023 initiative” (STCU project #9918), project “Development of a microbial test to evaluate the effect of geomagnetic field on biological systems”.Grant Agreement #99184

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ON THE FINITE-SIZE SCALING ABOVE THE UPPER CRITICAL DIMENSION: SPIN MODEL SIMULATIONS

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The upper critical dimension d_{uc} is a marginal space dimension below which a system experiences nontrivial critical behavior. Above this dimension, fluctuations become so small that they can be neglected, therefore the mean field approximation delivers exact results for the universal scaling exponents. While in the thermodynamic limit the scaling exponents around the phase transition point are indeed mean-field, the finite-size scaling (FSS) shows different results. The usual hyperscaling relation, $\nu d = 2-\alpha$, that combines the correlation length and heat capacity universal scaling exponents with the space dimensionality, also fails. These circumstances were argued by Fisher to be caused by the so-called dangerous irrelevant variables (DIV) that cannot be set to zero as one would do in the regular mean-field approximation. A new exponent *koppa* and subsequent Q-scaling was introduced by Kenna and Berche [1] to solve this discrepancy. Here, we consider the Ising model above the upper critical dimension $d_{uc}=4$.

While for lattices with periodic boundary conditions (PBC) the Q-scaling is valid at both critical and pseudocritical points, for free boundary conditions (FBC) two scaling regimes emerge, Gaussian (G-scaling) at critical point and Q-scaling at the pseudocritical point for each lattice size. This happens because of the shifting of the isothermal susceptibility in the systems of finite size, so that the effective critical behaviour occurs far from the critical point. The aim of this work is to find the critical exponents that will hint towards Q- or G-scaling in a 5-dimensional hypercubic lattice of Ising spins. We perform computer simulations to estimate FSS asymptotic and use other methods such as zeros of the partition function analysis to further refine the accuracy of the results [2,3].

The work was supported by the IEEE "Magnetism for Ukraine 2022/2023 initiative" (STCU project #9918).

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MAGNETIZATION DYNAMICS IN SUPERCONDUCTOR-FERROMAGNET BILAYERS

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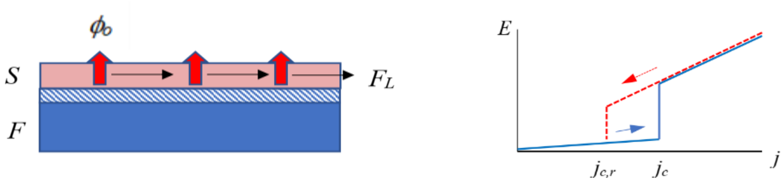
Hybrid superconductor/ferromagnet (S-F) multilayer thin-film structures are of great interest with respect to both fundamental physics and device applications. In the framework of this project, we explored thin film S/F bilayer structures, such as MoRe/Py and MoRe/Ni. Magnetization dynamics in these hybrid systems was studied in a dc regime by transport and at microwave frequencies using the resonator technique. For a dc regime, one of the problems which can be resolved by use of such S/F bilayer structure concerns pinning and dynamics of Abrikosov vortices in applied magnetic field. It is supposed that these vortices can be effectively pinned by magnetization inhomogeneity and/or magnetic polarons in F-layers, thus increasing the critical current value of superconducting films in this structure [1, 2]. On the other hand, as it was argued in some works (see, e.g. [3]), the motion of Abrikosov vortices in the flux-flow regime in S/F multilayer thin-film structures will cause generation of coherent magnons. So these effects, related to dynamic behavior of Abrikosov vortex lattice in S/F multilayer thin-film structures, look rather attractive for possible applications.

The enhancement of the vortex pinning and consequent increase of the critical current value in layered S-F thin film structures, which has been observed experimentally in some works [4], can be caused by the magnetic interaction of Abrikosov vortices with a static inhomogeneity of the magnetization in the F-layer [1] or by magnetic polarons, which can be induced by the vortex's own magnetic field, Hv(r,t), penetrating the F-layer perpendicular to the S/F boundary plane and forming a local spin polarization and corresponding local magnetization, M(r,t), of the F-layer around the vortex center position at the S/F boundary (see Fig. 1 (a)). These magnetic polarons, consisting of the Abrikosov vortices in the S-layer magnetically coupled to a cloud of local magnetization in the F-layer, can move under the action of the Lorentz force. In the flow regime at low currents, this motion can be characterized by increased viscosity due to polaron drag. As the current increases, the dissociation of this magnetic polaron should proceed, followed by a decrease in the viscosity coefficient, approaching the value of the Bardeen-

Stefen law for the pristine S-film. This dissociation type will manifest as a jump on the CVC of the S/F sample, similar to that shown in Fig1(b). This type of jump in the CVC can be considered as a critical depinning current associated with the dynamical decomposition of magnetic polarons in S/F bilayer under study.



(a) (b)

Fig.1. (a) – schematic presentation of a S/F bilayer with Abrikosov vortices in a perpendicular magnetic field; (b) - an expected CVC of the S/F bilayer narrow bridge in the polaron model

An experimental study of dc transport properties of S/F bilayers was performed by use of narrow superconducting thin film MoRe bridges, deposited over the Py plates and/or Ni films. The MoRe bridge’s width was about 10 nm, and the MoRe film thickness was ~100 nm. Obtained results for the CVC of these S/F structures measured in the magnetic field demonstrate the possibility of the critical current increase in such S/F structures, while the possibility of polaron dissociation effect manifestation on CVC of these samples is masked by thermally activated flux creep processes.

The microwave measurements on S/F bilayer systems were carried out by use of superconducting resonators with thin MoRe film deposited on the Py and/or Ni film. Obtained results indicate a strong photon-magnon interaction in such systems [5] and are under consideration now.

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THE MAGNONIC AHARONOV–CASHER EFFECT AND ELECTRIC FIELD CONTROL OF SPIN WAVES DYNAMICS IN FERRO- AND ANTIFERROMAGNETIC NANOSTRIPES

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Magnons are electrically neutral bosonic quasiparticles emerging as collective spin excitations of magnetically ordered materials, and they play a key role in the next generation of spintronics. Efficient control of magnon dynamics in magnetic nano-hetero-structures is critical for their practical application. One of the actively discussed methods is using an electric field, **E**. The **E**-field impact on the spin wave's (SW) dynamics in centrosymmetric magnetic insulators is based on a topological action known as the Aharonov-Casher (AC) effect [1]. In the linear order approximation, this effect can be accounted for by adding a term to the system's free energy expression like the Dzyaloshinskii-Moriya interaction. This topological quantum phenomenon has been directly detected experimentally for SWs propagating in the classical magnetic insulator $Y_3Fe_5O_{12}$ [2,3]. Thus, the electric field provides us with the possibility to control the dynamic properties of SWs in real time, which is a key component of magnonic devices. Through analytical calculations and micromagnetic simulations, we demonstrated that it is possible to control the SW characteristics using an external **E**-field [4-6].

This report examines the possibility of the **E**-field control of the refraction and reflection of coherently propagating SWs. This is done by studying the propagation of SWs across the boundary between two regions of a homogeneous ferromagnetic film under the influence of different external electric fields. We have derived an analytical expression for a magnetic Snell's law and performed micromagnetic simulations to demonstrate how the AC phase shift can control SW refraction [7]. This effect enables the experiment to quantify the topological AC phase action. The **E**-field effect on chirality-dependent spin-waves dynamics in a two-sublattice easy-axis antiferromagnet has been investigated, too [8,9]. It was shown that the **E**-field can split SWs of different chirality, and the splitting magnitude is proportional to the magnitude of the **E**-field. Furthermore, details are provided on the **E**-field effect on the propagation of SWs and their damping length. The attenuation of the given chirality magnons can be enhanced or weakened separately depending on the direction of the electric field. These findings could be useful for **E**-field-effect transistors or interferometric devices based on SWs. The AC effect has great potential for practical applications in quantum magnonics, opening a new way to control magnonic devices.

The results have been presented at the Bogolyubov Kyiv Conference "Problems of Theoretical and Mathematical Physics", September 24-26, 2024, Kyiv, Ukraine [10,11].

The work was supported by the IEEE "Magnetism for Ukraine 2023 initiative" (STCU project #9918), project entitled "The Aharonov-Kasher effect and an electric field control of magnetization dynamics in two-sublattice magnets."

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CONTROLLING ELECTRON KINETICS IN 2D MATERIALS BY NON-UNIFORM MAGNETIC FIELDS

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The hybrid nanostructures integrating spatially-periodic nanostructures with 2D semiconductor materials, such as graphene-like materials or van der Waals layers are of great interest to many researchers. Such hybrid nanostructures allow combining magnetic, electrical, optical, elastic, and other properties of nanogratings and 2D layers and transferring the periodicity to a whole hybrid system. As a result, hybrid nanostructures can have a variety of new exciting properties with potential applications.

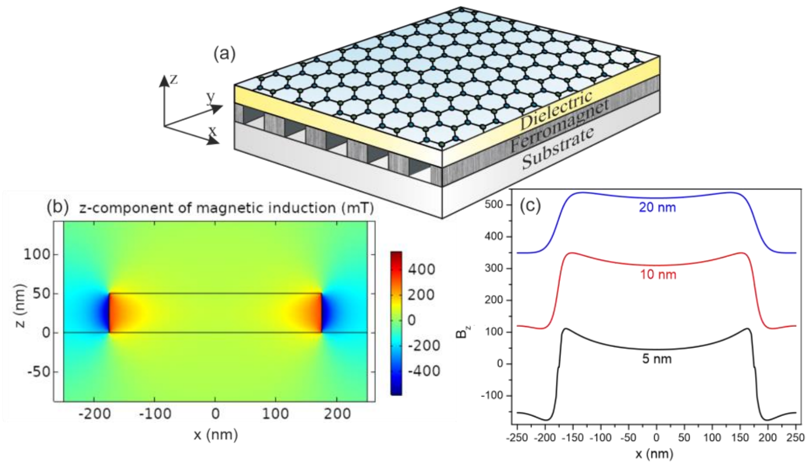

Fig. 1. (a) Sketch of the structure and the coordinate system. (b) Spatial distributions of the z-components of the magnetic inductions generated by ferromagnetic nanogratings in the case of an external magnetic induction of 1 T parallel to the z-axis. (c) Dependence of the magnetic induction on the *z*-coordinate at distances of 5, 10, and 20 nm from the nanogratings.

We considered a system of graphene-like material deposited on the ferromagnetic nanogratings (see Fig. 1(a)). The latter can generate a non-uniform magnetic field (see e.g. [1]). Indeed, Figs 1(b), (c) show that the magnetic induction is spatially non-uniform and its value is maximal near the boundary of the ferromagnet/nonmagnetic materials (B_z ~100 mT) and decreases with distance from the ferromagnetic nanogratings. The electrons in the conductive layer of the graphene-like material are sensitive to magnetic induction due to the Lorentz force acting on electrons in graphene.

We developed the theory of high-frequency magnetotransport in graphene-like materials in non-uniform magnetic fields. The complex local conductivity tensor of electrons in graphene-like materials in the non-uniform magnetic field is found. Using this conductivity, the optical characteristics, namely transition, reflection, absorption coefficients, and angle of rotation of the polarization plane are found. Obtained results indicate that non-uniform magnetic field changes the optical characteristics (Fig. 2(a)) due to nonuniform magnetic fields. Especially it changes the rotation angle to up to 20 % for considered parameters (Fig. 2(b)) in comparison with the case $\delta B = 0$. The magnitude of the effects depends on the ratio, δB, between the amplitude of the non-uniform magnetic induction and the external magnetic induction.

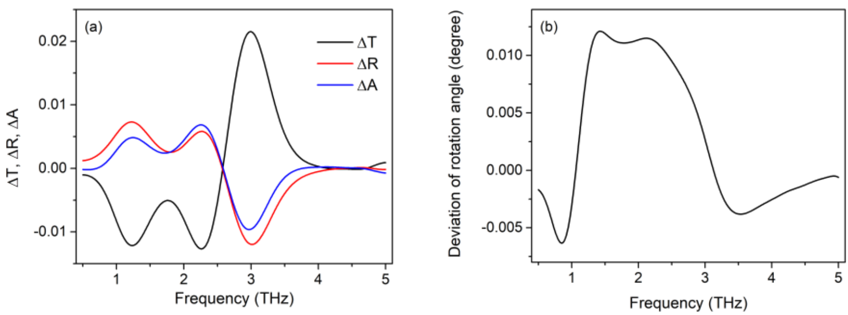

Fig. 2. Deviations of transition, ΔT, reflection, ΔR, absorption, ΔA, coefficients (a), and rotation angle (b) as a function of frequency at the external magnetic induction 1 T and non-uniform magnetic induction ($\delta B \approx 0.15$).

Additionally, we considered the plasmonic crystal, where each grating wire played the role of a gate, which allowed us to control the electron concentration in the conducting layer. As a result, two different plasmonic crystal phases were achieved experimentally and explained theoretically [2].

The work was supported by the IEEE "Magnetism for Ukraine 2022/2023 initiative" (STCU project #9918), project entitled "Controlling electron kinetics in 2D materials by non-uniform magnetic fields".

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INFLUENCE OF LOCAL-FIELD EFFECTS ON THE OPTICAL RESPONSE OF MAGNETO-PLASMONIC SYSTEMS

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Brillouin light scattering (BLS) spectroscopy is a powerful tool for detecting spin waves in magnetic thin films and nanostructures [1]. Despite of advanages to study of spin-wave properties, BLS spectroscopy suffers from the typically relatively low sensitivity. To solve the problem of amplification of BLS response, it is possible with assistance of nanoplasmonic structures at the surface of magnetic film. The analytical approach to calculate the optical response of magneto-plasmonic systems was developed. The approach is based on the effective susceptibility concept [2] in the frame of electrodynamic Green's function method, which takes into account the key contribution of local-field effects in the formation of the response of a plasmon system located on the surface of a magnetic film. The oscillating electrodipole momentum inside a thin magnetic film due to photon-magnon interaction [3] is considered as the source of optical response at the shifted frequency. Based on the solution of equation of self-consistency (so called Lippmann-Schwinger equation), effective susceptibility (linear response to the external field) of the magnetoplasmonic system is obtained [4]. In particular, the effective susceptibility for the nanoplasmonic structure consisting of three 'nanodiscks' has a form

$$X_{ji}^{(S)}(\mathbf{R}^{(\alpha)},\omega)=\left\{\left[\chi_{ji}^{(\alpha)}(\omega)\right]^{-1}+k_0^2\int\limits_{V_\alpha} d\mathbf{R}'G_{ij}^{(33)}(\mathbf{R}',\mathbf{R}^{(\alpha)},\omega)+\right.$$
$$\left.+k_0^2\sum_{\beta\neq\alpha}\int\limits_{V_\beta} d\mathbf{R}^{(\beta)}G_{ij}^{(33)}(\mathbf{R}^{(\beta)},\mathbf{R}^{(\alpha)},\omega)\right\}^{-1},\qquad \alpha,\beta=1,2,3\,, \tag{1}$$

with $G_{ij}^{(33)}(\mathbf{R}',\mathbf{R}^{(\alpha)},\omega)$ electrodynamic Green's function of the magnetic film at the substrate, $\chi_{ji}^{(\alpha)}(\omega)$ dielectric response of the material of α-th nanoparticle, integrations are over nanoparticle volumes. Using Eq.(1) the analysis of a possible morphology of nanoplasmonics structures suitabling enhance the BLS was performed. As a example the optimization map of the morphology of the silver plasmon structure consisting of two nanoparticles shaped as ellipsoids of

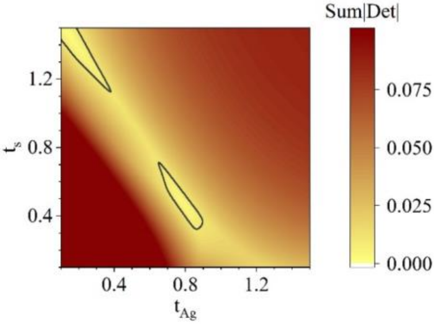

Fig.1. The optimization map of the morphology of the silver plasmon structure consisting of two nanoparticles shaped as ellipsoids of rotation with the ellipsoidal dielectric spacer. t_s and t_{Ag} are the eccentricities of spacer and metal nanoparticles, respectively.

rotation with the ellipsoidal dielectric spacer is presented in Fig.1. The domains of optimize morphology of nanostructure giving the BLS enhancing are restricted by black lines. The practical implementation of the results of this work is beyond the scope of our research. Note that the effect of BLS amplification considered in this work is related to the redistribution of the local field in the magnetic film and the nanostructure.

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INFLUENCE OF MECHANICAL STRESS AND MAGNETIC FIELD ON MAGNETOELASTIC AND MAGNETOELECTRIC PROPERTIES OF MAGNETIC SHAPE MEMORY ALLOYS AND MSMA-BASED MATERIALS

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In this communication the scientific results obtained in the course of Project no. 9918 performance are presented.

A dynamic mechanical analysis (DMA), magnetic and electric measurements are commonly used for characterization of the *first-order ferroelastic phase transitions referred to as martensitic transformations* (MTs) of magnetic shape memory alloys (MSMAs) (see [1] and references therein). The tendency to minimization of total elastic energy and mechanical stresses of product (martensitic) phase of MSMA results in the microtwinning of crystal lattice. A significant disparity between MT temperatures estimated for Ni-Fe(Co)-Ga alloy from DMA and those determined from magnetic and resistivity measurements was discovered in the course of the Project performance It was argued that the discrepancy is caused by the variable mechanical stressing of twinned single crystalline MSMA by the DMA analyzer. Moreover, the DMA measurements revealed an unusually significant (by 20%) decrease of the elastic modulus of twinned martensite under the applied magnetic field of 1.5 kOe. To explain this effect, the temperature-dependent Young's modulus of twinned crystal lattice was computed. The computations showed that the observed field-induced change of Young's modulus results from the stress-assisted detwinning of crystal lattice in the applied magnetic field. These results are published in [1].

Ni-Mn-Ga alloys are the most representative MSMAs. The ferromagnetic resonance measurements carried out in the course of Project performance resulted in the discovery of new mechanism of formation of giant (corresponding to anisotropy field of 4 kOe) *four-fold* magnetic anisotropy of elastically twinned Ni-Mn-Ga epitaxial film. It was shown theoretically that the observed giant magnetic anisotropy is caused by the spin-exchange coupling of twin components with the nonparallel symmetry axes, and therefore, nonparallel magnetization vectors. It was argued that the experimentally determined magnetic anisotropy field exceeds the anisotropy field caused by magnetoelastic coupling. These results are published in [2].

The P(VDF-TrFE) piezopolymer is one of intensively studied *magnetoelectric* (ME) materials (see [3] and references therein). The variable magnetic field, applied to this piezopolymer, induces ME signal. The incorporation of *martensitic* Ni-Mn-Ga particles into the P(VDF-TrFE) film results in amplification of ME signal by one order of magnitude, to the value of about 4 V $cm^{-1}Oe^{-1}$ [3]. In accordance with the Project topic the temperature interval of giant magnetoelectric (ME) effect experimentally observed in Piezopolymer/Ni-Mn-Ga composite material was determined. To this end the amplitude of magnetoelectric signal induced by the variable magnetic field in P(VDF-TrFE)/Ni-Mn-Ga composite was measured in the temperature interval from 298 K to 328 K. This interval includes the temperature range of MT of Ni-Mn-Ga particles. It was shown that the *martensite – austenite* phase transition in Ni-Mn-Ga particles amplifies ME signal from 4 V $cm^{-1}Oe^{-1}$ to 20 V $cm^{-1}Oe^{-1}$.

Theoretical analysis of magnetoelectric properties of P(VDF-TrFE)/Ni-Mn-Ga composite suggested idea that the incorporation of Ni-Mn-Ga particles into P(VDF-TrFE) polymer may enhance a *pyroelectric* (PE) effect, which is inherent to this polymer. Doe to the Project performance this idea was confirmed experimentally: pyroelectric voltage measured at P(VDF-TrFE)/Ni-Mn-Ga film proved to be higher than that measured at P(VDF-TrFE) film by factor 2.5. It was shown theoretically that PE voltage increases due to the mechanical stressing of piezopolymer by the Ni-Mn-Ga particles, which undergo strong deformation in the temperature range of martensitic transformation.

The work was supported by the IEEE Magnetics Society, "Magnetism for Ukraine initiative" (STCU project #9918), project entitled "Combined influence of variable mechanical stress and magnetic field and on the elastic and magnetoelectric properties of magnetic shape memory alloys and MSMA-based materials". V.A.L. acknowledges funding by the Ministry of Education and Science of Ukraine (project 0124U000392).

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MAGNETIC FIELD EFFECT ON RESONANT PROPERTIES OF SURFACE PLASMON-POLARITON PHOTODETECTORS

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The semiconductor plasmon-polariton photodetectors (PPPD) is a structure with a built-in near surface potential barrier. It can be a shallow *p-n* junction or a Schottky barrier with a metal front contact (usually Au or Ag) that is periodically profiled in the form of a diffraction grating (DG). It is this microrelief that fundamentally allows the excitation of surface plasmon resonance (SPR), thanks to the matching of the wave vector of the surface plasmon polariton wave and light. Up to now [1] there are a number of high-quality and ultra-highly sensitive sensors, which based on SPR basis sensor system. But all of them are required additional substance – some magnetic fluid as the magnetic sensitive material, which is sensitive to external magnetic field (MF) and plays the role of the external environment that besides main metal material defines of SPR-peak position. Any changing in magnetic properties of this magnetic fluid results in the changing of SPR signal. But SPR signal can be able to sense the MF action without any additional magnetic fluid due to well-known Lorenz force, which appeared in magnetic fields and rotate electrons with cyclotron frequency resulting in the change of position of SPR-related peak.

There were three configurations of applied magnetic fields in our investigation (at magnetic flux density 100 and 300 mT). At the first position MF was parallel (antiparallel) to the normal of sample surface and to the incident beam plane, while at the second one it was perpendicular to this normal and at the same time perpendicular to the incident beam plane. At the third position MF was perpendicular to the normal of sample surface and at the same time parallel to the incident beam plane. The optical properties of DG were studied at room temperature by spectroscopic ellipsometry (SE) within (190…2000 nm) spectral range and angles from 70° to 20° with a resolution of 1 nm. The experimental ellipsometry angles (Ψ, Δ) are defined by the complex reflectance ratio $\rho = r_p/r_s = tan\,\psi\, e^{i\Delta}$, where r_p and r_s are the complex Fresnel reflection coefficients for *p*- and *s*-polarized light, respectively. tan (ψ) represents the amplitude ratio of the *p*- and *s*-components of reflected light and Δ describes the phase difference between *p*- and *s*-polarized light.

Maximal spectral shift, which was detected due to MF action was observed in the position II and was as large as 8 nm. This corresponds to 13 meV for observed blue shift of the plasmon-polariton wave from 880 to 872 nm for field in position II. For III and I positions these values are 9.7 meV (from 880 to 874 nm) and 4.8 meV (from 880 to 876 nm), respectively.

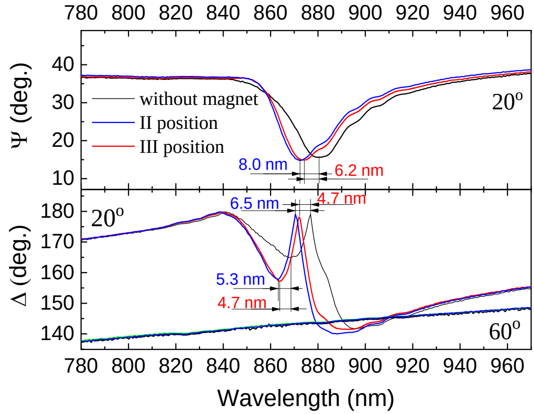

Fig. 1. Experimental Ψ and Δ *vs* wavelength dependences obtained at II and III positions for the incident angle of 20° and 60°.

Besides detected blue shifts in plasmon resonance spectral region, red shifts as large as 10-11 nm for Positions II and III also were detected. These red shifts were observed in non-SPR spectral range while blue shifts were detected near plasmon frequencies. Observed features looks like complicate and required further investigation. The opposite influence of the same magnetic field on peaks in different spectral ranges is unexpected. But we tend to explain these phenomena within the concept of the optical Hall effect. The results and conclusions of this study can be summarized as follows. (i) Magnetic field induced effects were detected in non-magnetic composition of PPPD. (ii) The observed features are disappeared when magnetic field action was removed. (iii) The most significant effect of the magnetic field action on the spectral extremes positions is observed at the incident angle of 20°. (iv) At the sample position II magnetic field induced effect was greater than that in position I and III.

The work was supported by the IEEE "Magnetism for Ukraine 2023 initiative" (STCU project #9918), project entitled "Magnetic field effect on resonant properties of surface plasmon-polariton photodetectors".

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MAGNETISM OF HIGHLY DOPED CdTe:Cr CRYSTALS WITH QUASI-2D DOPANT-RELATED PRECIPITATES

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In our previous investigations of the heavily doped CdTe:Cr single crystals, grown by the modified PVT method, we revealed the doping-induced crystallographic phase separation due to the exceeding of Cr solubility limit in this compound [1]. Energy dispersive X-ray spectroscopy microanalysis and mapping, electron diffraction and high-resolution transmission electron microscopy revealed the formation of the array of platelet precipitates of monoclinic Cr_3Te_4. They developed on the {111} planes of CdTe matrix during the post-grown cooling of the crystals as the result of Cr precipitation due to the overall super-saturation of the matrix with this element. The orientation relation was found to be $(100)_{Cr_3Te_4}//(111)_{CdTe}$ and $[011]_{Cr_3Te_4}//[01\bar{1}]_{CdTe}$.

In the present work, the magnetic properties of such heterogeneous material were studied thoroughly by determining the contribution from the host semiconductor phase as well as from the precipitated Cr-related particles. The ferromagnetism of the CdTe:Cr crystals was revealed in the range from liquid nitrogen temperature to above room temperature by magnetization measurements using a vibrating sample magnetometer and by the Faraday method. The analysis of the magnetization temperature dependence indicates the presence of several magnetic phases in the material, including Cr_3Te_4 one. Curie temperature, derived by fitting the temperature dependence of inverse magnetic susceptibility with Curie-Weiss law, was found to be 400 K.

Off-axis electron holography experiments proved that the observed ferromagnetic behavior is mainly governed by the embedded Cr_3Te_4 particles, although a weak contribution of the $Cd_{1-x}Cr_xTe$ matrix itself to the overall ferromagnetism can be also supposed from the magnetization measurements. Moreover, electron holography revealed magnetic anisotropy of the precipitates, their easy magnetic axis is perpendicular to the [101] crystallographic direction. The above suggestions were confirmed by the results of the electron magnetic resonance studies. The EMR spectra consisted of multiple lines found to originate from both Cr atoms dissolved in the CdTe crystalline lattice and from Cr-related extrinsic phases. The lines coming from the Cr_3Te_4 lamellas were distinguished in the spectra at a high magnetic field. Their angular dependences show six-fold symmetry, which originates from both the magneto-crystalline and shape anisotropies of the precipitates.

Since the thickness of the above Cr_3Te_4 platelet precipitates starts from tens of nm and their lateral dimensions reach half of the mm, they can be considered as quasi-2D magnets buried in the host CdTe matrix. Gaining the 2D magnetic materials is crucial for the development of next-generation spintronic devices [2]. Chromium tellurides have attracted immense interest in the recent few years, because of their chemical stability in ambient and ability to retain magnetic ordering at room temperature down to the monolayer [3]. 2D layers of these compounds are currently fabricated by epitaxial growth of ultrathin Cr_xTe_y layers on the different substrates using CVD or MBE techniques. The results of our studies indicate the possibility of using precipitation of ferromagnetic 2D phases as an effective tool and a cheaper alternative for semiconductor-based composites and semiconductor-ferromagnetic junction fabrication.

The work was supported by the IEEE “Magnetism for Ukraine 2022/2023 initiative” (STCU project #9918), project entitled “Magnetism of (Cd,Cr)Te semiconductor crystals with self-assembled Cr-related doping-induced nanoprecipitates”. EMR investigations were performed in the frame of International Research Travel Award Program (IRTAP-Ukraine) from American Physical Society and Alfred P. Sloan Foundation (V.D. Popovych).

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GENERATORS OF HARMONIC AND STOCHASTIC SIGNALS BASED ON ANTIFERROMAGNETIC SPIN HALL OSCILLATORS

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Antiferromagnetic (AFM) spintronics is a promising field of modern magnetoelectronics [1-3]. The AFM devices utilize ultrafast magnetic dynamics in the frequency range of about 50 – 10^4 GHz. Antiferromagnets (AFMs) are also insensitive to dc magnetic fields and do not affect the surrounding electronic components via dc magnetic fields, which can be promising for embedding AFM devices in various micro- and nanoelectronic systems.

AFM-based signal generators are typically designed as AFM/heavy metal (HM) bilayers (or even multilayers) known as spin Hall oscillators (SHOs) [1-7]. Due to the spin Hall effect, when a dc electric current flows through the HM layer of an AFM SHO, it induces the perpendicular spin current, which, in turn, excites the rotation of magnetic sublattices in an adjacent AFM layer of a SHO. The sublattice rotation leads to the generation of (sub-)terahertz signals, the power of which can be extracted using various mechanisms (see review [3]).

The signal power that can be generated and extracted from a single AFM SHO is usually around 1 μW or even less, which limits the area of practical applications of AFM SHOs. To overcome this bottleneck, a signal source with multiple generating SHOs has been proposed in [5] and then extended in the framework of the IEEE Magnetism for Ukraine project. We propose to embed an array of AFM SHOs in a high-Q dielectric resonator (as was done for a

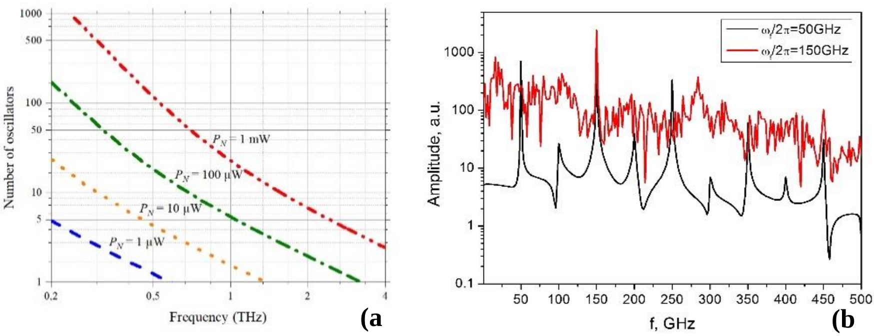

Fig. 1. **a** Frequency dependence of the number of perfectly coupled SHOs required to achieve the specified powers; **b** Output AFM SHO signal spectrum under the action of the ac signal with different frequencies.

single SHO in [6]). In our calculations we use magnetic wall boundary conditions at the resonator edges and consider the SHOs with canted AFM layers as radiating magnetic dipoles. The obtained results for the total output ac power of the considered source show that it is possible to generate signals of even 1 mW power in a system with a small number (≤ 10) of synchronized AFM SHOs (Fig. 1a).

Another problem analyzed within the IEEE Magnetism for Ukraine project was the development of an AFM-based stochastic generator. We found that the Josephson-like AFM SHO biased by a purely harmonic signal can act as a source of stochastic signal [7]. The nature of such a generation regime can be explained by the random hopping of the working point of the SHO between several quasi-stable states under the action of an applied ac current. We reveal that, depending on the frequency / amplitude ratio of the external ac signal, several stochastic generation regimes interspersed with regular generation regimes can be achieved (Fig. 1b). Such behavior can be used in spintronic random signal sources and various nanoscale random signal devices, including the spintronic p-bit device considered in [7].

The work was supported by the IEEE "Magnetism for Ukraine" initiative (STCU project #9918), projects entitled "Chaotic magnetization dynamics in antiferromagnetic spin Hall oscillators for cryptography applications" and "High-performance terahertz signal sources based on antiferromagnetic spintronic nanostructures".

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THE NATURE OF ELECTRICALLY DETECTED MAGNETIC RESONANCE IN HIGHLY NITROGEN-DOPED 6H SiC SINGLE CRYSTALS

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Silicon carbide (SiC) is a wide-bandgap semiconductor widely used in high-performance power electronics, optoelectronics, and emerging quantum devices due to its remarkable physical and electrical properties. Among its various polytypes, 6H-SiC stands out for its stability, thermal conductivity, and mechanical strength, making it crucial in applications requiring high thermal stability and power handling.

Nitrogen (N) doping is a standard method to modify the electrical properties of SiC; however, understanding the interaction between N donors and the spin-related phenomena at high doping concentrations remains an open question, especially in n-type 6H-SiC.

This study provides new insights into the electron paramagnetic resonance (EPR) and electrically detected magnetic resonance (EDMR) of highly N-doped 6H-SiC single crystals, which is fundamental for optimizing materials for spintronic and quantum information applications.

Two sets of n-type 6H-SiC single crystals with uncompensated N donor concentrations of $N_D - N_A \approx 8\times10^{18}$ and 4×10^{19} cm^{-3} grown using the modified Lely method were studied. Multifrequency EPR spectroscopy (9.4–395.12 GHz) and high-frequency EDMR (100 GHz) measurements were performed at low temperatures (down to 5 K) to investigate the spin-dependent processes in these highly doped crystals. The EPR spectra were simulated using the spin Hamiltonian formalism, allowing for precise determination of the *g*-tensor and hyperfine interaction constants of the N donors.

The EPR measurements revealed the presence of three paramagnetic centers: an intense S line and an S1 line, as well as a low-intensity triplet corresponding to nitrogen (N) donors at the quasicubic “k2” position (N_{k2}). The hyperfine interaction constants for N_{k2} donors were determined to be $A_{\perp} = A_{\parallel} =$ 1.11 mT, which are slightly lower than those found in lower-doped samples, possibly due to deviations from stoichiometry in heavily N-doped 6H-SiC crystals. The S line was assigned to the exchange coupling of conduction electrons with N donors at quasicubic “k2” positions, characterized by $g_{\perp} =$ 2.0029(2) and $g_{\parallel} = 2.0038(2)$. The S1 line, $g_{\perp} = 2.0030(2)$ and $g_{\parallel} = 2.0040(2)$, was attributed to exchange interactions between localized N donors at the “k1” and “k2” positions, observed in the EDMR spectra of the sample with $N_D - N_A \approx 8\times10^{18}$ cm^{-3}.

The EDMR measurements indicated that the appearance of this signal is related to enhanced hopping conductivity due to the EPR-induced temperature increase mechanism. Notably, no EDMR signals were detected in the crystals with $N_D - N_A \approx 4\times10^{19}$ cm^{-3}, suggesting that this concentration is too high for the spin-dependent scattering to occur but insufficient for the appearance of the EPR-induced hopping mechanism.

Thus, the emergence of EDMR signals in nitrogen-doped 6H-SiC single crystals depends critically on the nitrogen concentration. In crystals with a concentration of $\approx 8\times10^{18}$ cm^{-3}, spin-dependent hopping conductivity was enhanced due to an EPR-induced temperature increase. The observed S1 line in the EDMR spectra corresponds to the exchange spin interaction between N donors at different quasi-cubic lattice positions, confirming the role of spin interactions in the electrical transport properties of these highly doped SiC materials.

For higher doping levels (4×10^{19} cm^{-3}), the absence of EDMR signals indicates that the system is approaching the semiconductor-metal transition, where conduction becomes dominated by band-like transport, rendering spin-dependent mechanisms less significant. This result is crucial for designing high-power and quantum devices based on SiC, where precise control of donor concentration is essential for optimizing device performance.

The work was supported by the IEEE “Magnetism for Ukraine 2023 initiative” (STCU project #9918), the project entitled “Magnetic interactions and spin dynamics in heavily nitrogen-doped 6H SiC monocrystals”.

MANIPULATION OF MAGNETIZATION TEXTURES IN CURVED NANOWIRES AND STRIPES

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The aim of the project was to study (theoretically and numerically) geometry-induced effects in ferro- and antiferro- magnetic nanowires and narrow ribbons. The project aimed to provide new information about the design of magnetic nanostructures and achieve the control of magnetization dynamics in them. The following investigations were provided within the scope of the project.

As a first task we presented a generalized micromagnetic framework of curvilinear wires and stripes with varying cross section, e.g., with thickness and (or) width gradients [1]. We applied the theory to predict the effects in the static and linear dynamics of domain walls in curved stripes with varying cross section. In particular, the domain wall can be pinned by local cross-section deformation; the eigenfrequencies of the domain wall free oscillations at the pinning potential are determined by both curvature and cross-section gradients.

Our second task was to manipulate domain wall dynamics in a curved antiferromagnet spin chain by a rotating magnetic field [2]. Namely, we investigated theoretically the interplay between geometrical and magnetic field effects in intrinsically achiral anisotropic spin chains shaped as rings and helices exposed to uniform static and rotating magnetic fields. We predicted the existence of two topologically different ground states in ring-shaped antiferromagnets depending on the curvature due to the influence of curvature-induced Dzyaloshinskii–Moriya interaction. In the helix-shaped spin chain, we found that a rotating magnetic field induces domain wall propagation with velocity, which is proportional to the field frequency. Curvature and torsion strongly influence domain wall velocity and stability conditions of the motion.

As a third task we analyzed the automotion of domain wall in ferromagnet ribbons with variable thickness [3]. We described how tailoring the cross-sectional area of ferromagnetic nanostripe influences the dynamics of domain wall motion: the gradient of thickness can become an alternative cause of domain wall movement, which can explain the recent experimental results.

The last task was about controlled dynamics of domain walls in antiferromagnetic stripes with functionally graded Dzyaloshinskii–Moriya interaction [4]. We studied the dynamic properties of domain walls in antiferromagnet with functionally-graded Dzyaloshinskii–Moriya interaction under the action of external rotating magnetic field. The domain wall was found to be pinned at position, which essentially depends on the frequency of external rotating field. This provides efficient ways to control domain wall pinning position by changing external field frequency.

The work was supported by the IEEE “Magnetism for Ukraine 2022 initiative” (STCU project #9918), project entitled “Manipulation of Magnetization Textures in Curved Nanowires Title”.

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MAGNETIC COUPLING READOUT BASED ON A FLUX QUBIT WITH RF SQUID FOR MAGNONICS

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Detectors based on superconducting qubits and qudits (mesoscopic structures with discrete energy levels) using the method of non-destructive continuous quantum measurements [1]. Coupling such structures with ferromagnetic elements or layouts that operated with spin waves will allow us to develop manipulations in quantum magnonics. In order to minimize back-action of readout system [2, 3], it is proposed to use the superconducting quantum interferometer detectors with one Josephson junction (so called RF SQUID) that inductively (magnetically) coupled with quantum system [4].

Magnonics, as an analogue to photonics and phononics, offers significant advantages. Spin waves transmit information through the material without causing heating, making magnonic systems more energy-efficient. They also have shorter wavelengths, enabling the creation of smaller devices, easier integration into modern technologies, and programmability for various functions. Elements such as magnonic memory, transistors, microwave filters, diodes, and circulators have already been proposed, showcasing the potential of magnonics in electronics and logic circuits. Furthermore, magnonic system can be integrated with other quantum platforms, for example, photons, qubits, and phonons to achieve hybrid quantum systems [5]. These hybrid platforms benefit the advantages of magnonic system and can be utilized to achieve multifunctional tasks of information processing in both the classical and quantum levels [6].

Here we discuss the operational scheme of such hybrid system where establish the entanglement states among magnon generated subsystem and qubit – SQUID-readout system as detectors of spin-wave excitations.

Previously such scheme of qubit – SQUID-readout system was proposed as the tunable detector of the microwave photons [7]. Since magnons generate variable magnetic fields during spin wave propagation, our readout part can detect these small magnetic flux changes with exceptional precision. Due to magnetic coupling of superconductive and magnonic subsystems through the planar structure and mutual inductivity we can minimize interaction among them. This allows for the study of magnon behavior and the dynamics of spin waves in magnetic materials. The reduction of magnetic coupling and using of non-dispersive mode of SQUID operation ensure to fulfill weak continuous measurement. Generation of spin waves in this case can be fulfilled by the laser beam scaning or magnetization dynamics in thin films structures [8].

The interaction between magnons and qubit – SQUID-readout system opens up promising opportunities for the development of quantum technologies, including the control and transmission of information via spin waves. This integration holds great potential for spintronics, quantum computing, and next-generation information technologies..

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INFLUENCE OF EXTERNAL MAGNETIC FIELD ON THE MORPHOLOGY AND STRUCTURAL CHARACTERISTICS OF COBALT-BASED THIN FILM SYSTEMS

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The magnetism of thin-film systems is an important area of condensed matter physics from both fundamental point of view and for practical applications in the fields of spintronics, biotechnology, etc. The rapid development of nanoelectronics and spintronics has caused considerable interest in the creation of new film structures with required physical properties and stable parameters under influence of various factors, including heat treatment, magnetic field, etc. The effects of external magnetic field influence which significantly modify the structure and properties of nanomaterials, should be taken into account for designing nanoelectronic devices operating under the influence of magnetic fields. Even minor changes in the structure or surface morphology of the films can lead to device failure. Understanding such effects will ensure the stability of spintronics devices.

The results of experimental studies of the effect of an external magnetic field on the morphology and structural characteristics of three different cobalt-based thin-film magnetic structures were presented: a single-layer Co film, a three-layer Co/Gd/Co film, and granular film alloys Co-Ag and Co-Cu. The results of the research were published in [1, 2]. The studies made it possible to establish the main regularities of the magnetic field effect on such structural characteristics of the surface of granular magnetic films as the height of the highest peak h_{max}, the depth of the deepest depression h_{min}, the arithmetic mean R_a and the root mean square R_q of the film surface roughness, and the structural entropy *S*. AFM studies have shown that the morphology of the films surface is locally inhomogeneous at the nanoscale and changes when an external magnetic field is applied. The largest influence of magnetic fields on the surface morphology and structural parameters of the film was observed in the non-annealed samples granulated Co-Ag film alloys. For instance, during the first application of an external magnetic field in the granulated Co-Ag films, a reduction in roughness parameters R_a by 19%, R_q by 16% (Fig.1a), structural entropy *S* by 4.5%, and the height of the highest peak by 4 times were observed. In the case of annealed at 800K samples granulated Co-Cu film alloys and homogeneous magnetic film structures, the effect was less pronounced. For the annealed $Co_{21}Cu_{79}$ sample, the first application of magnetic field with H = 0.5 kOe causes a decrease in the parameters R_a by 8.5%, R_q by 6.5%, and *S* by 6.5% (Fig.1b). For the single-layer Co film, a decrease in parameters R_a by 6%, R_q by 8%, and *S* by 1.3% was observed.

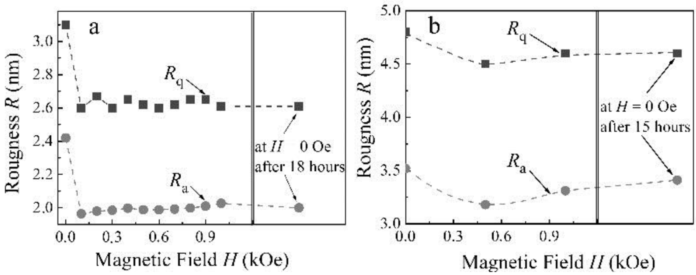

Fig.1. Dependence of the roughness values R_a and R_q of the non-annealed $Co_{39}Ag_{61}$ (a) and annealed at T=800 K $Co_{21}Cu_{79}$ (b) thin films on the magnitude of the external magnetic field. The film thickness d = 35 nm.

A further increase of the magnetic field practically did not affect the structural characteristics of the Co-Ag and Co-Cu film systems, which remained constant, even after relaxation for 15 and 18 hours (Fig.1). However, the surface morphology of the sample changed with the variation of the magnetic field intensity.

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MULTIFUNCTIONAL Fe_3O_4@CeO_2 NANOCOMPOSITES: SYNTHESIS, PHYSICO-CHEMICAL PROPERTIES AND BIOACTIVITY ASSESSMENT

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Inorganic metal oxide NPs such as Fe_3O_4 or CeO_2, which can possess some bio-functionality such as antimicrobial, antiviral, anti-inflammatory, or antioxidant activities [1], are of particular interest in the scope of their possible biomedical application. It is worth noting that the bio-functionality of inorganic NPs is often caused by oxidative stress. For example, Fe_3O_4 NPs can stimulate reactive oxygen species (ROS)-producing enzymes and promote the formation of oxidative stress that induces bacterial and viral death [1]. However, the formation of ROS is an uncontrolled process; their excess can damage and destroy normal healthy cells and tissues. To tackle this issue, we propose to synthesize the combined nanocomposites, in which magnetic Fe_3O_4 NPs will be coated with the CeO_2 shell that has pronounced antioxidant action. It is expected that these nanocomposites can consolidate various properties or even exhibit some new qualities due to the appearance of so-called "synergetic" effects.

This study was aimed at synthesizing magnetic Fe_3O_4@CeO_2 "core@shell"-like nanocomposites (NCPs) and examine their physico-chemical properties and bio-activity.

Fe_3O_4@CeO_2 with the theoretically calculated thickness of CeO_2-"shell" of 3-, 5-, and 7-nm were synthesized by the precipitation of CeO_2 NPs on the surface of pre-synthesized magnetic Fe_3O_4 NPs. XRD and XPS results suggested the formation of a "core@shell"-like structure that was validated by electron microscopy data (Fig. 1): synthesized Fe_3O_4@CeO_2 NCPs include Fe_3O_4 NPs "core" surrounded by ultra-small CeO_2 NPs (3.0-3.5 nm). XPS data verified the co-existence of two redox couples, Fe^{2+}/Fe^{3+} and Ce^{3+}/Ce^{4+}, on the surface of the NCPs and pointed to the occurrence of some redox interactions between them. The hydrodynamic diameter and colloidal stability of the synthesized Fe_3O_4@CeO_2 NCPs were examined using the DLS method. The collected results also indicated the formation of the nanocomposites: i) the hydrodynamic diameter of the NCPs grew with the increase in the CeO_2 "shell" thickness, ii) the surface charge of NCPs was positive that is typical for CeO_2 NPs while the bare Fe_3O_4 NPs were negatively charged. In addition, the appearance of CeO_2 increased the stability of the nanocomposites in the aqueous suspensions (zeta potential values become higher than +30 mV). The appearance of the CeO_2 shell around magnetic NPs decreases their magnetization values. However, such nanocomposites save their ability to heat in an alternating magnetic field [2].

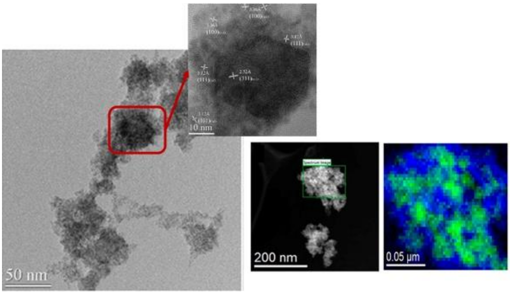

Figure 1. Representative TEM images and elemental distribution for Fe (blue) and Ce (green) for Fe_3O_4@CeO_2 NCPs [2]

The synthesized Fe_3O_4@CeO_2 NCPs showed a significant increase in the bio-activity (catalase- and superoxide dismutase-like activity), which indicates the antioxidant potential of nanocomposites compared to the individual Fe_3O_4 and CeO_2 NPs, and their bioactivity directly increased with growing CeO_2 "shell" around Fe_3O_4 NPs. Such synergy in properties is expected to be connected with the physico-chemical parameters of nanocomposites, in particular, with the balance of Fe^{2+}/Fe^{3+} and Ce^{3+}/Ce^{4+} on the surface.

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LONG-RANGE CORRELATIONS AND MAGNETISM OF SPINOR ULTRACOLD ATOMIC GASES

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In context of quantum gases, we obtain a many-body Hamiltonian for spin-3/2 atoms in a magnetic field with general multipole (spin, quadrupole, and octupole) exchange interaction by employing the apparatus of irreducible spherical tensor operators. This Hamiltonian implies the finite-range interaction, whereas for zero-range (contact) potentials parameterized by the s-wave scattering length, the multipole exchange interaction becomes irrelevant. Following the reduced description method for quantum systems, we derive the quantum kinetic equation for spin-3/2 atoms and apply it to examine the high-frequency oscillations also known as zero sound [1]. We further develop the general collisionless kinetic approach to studying excitations in arbitrary-spin quantum atomic gases [2].

For the interacting high-spin Fermi gases in optical lattice potentials, we study SU(4)-symmetric ultracold fermionic mixture in the cubic optical lattice with the variable tunneling amplitude along one particular crystallographic axis in the crossover region from the two- to three-dimensional spatial geometry. To theoretically analyze emerging magnetic phases and physical observables, we describe the system in the framework of the Fermi-Hubbard model and apply dynamical mean-field theory. We show that in two limiting cases of spatial anisotropy there are two phases with different antiferromagnetic orderings in the zero temperature limit and determine a region of their coexistence. We also study the stability regions of different magnetically-ordered states and density profiles of the gas in the harmonic optical trap [3]. We also study cases of explicit breaking of SU(4) spin symmetry by considering two different amplitudes of the on-site interaction between different spin flavors, as well as the case of different hopping amplitudes. In the strong-coupling limit, we obtain explicit expressions for the nearest-neighbor magnetic couplings in the corresponding Heisenberg-type effective spin models and calculate the respective energy spectra. Additionally, we analyze the effect of the symmetry breaking on the entropy distribution and the real-space separation of atoms in the harmonic trap [4].

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INFLUENCE OF INITIAL DISORDER ON THE STOCHASTIC FORMATION OF FERROELECTRIC DOMAIN STRUCTURE

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Formation of ferroelectric domain structure after the quenching of the sample from the high-temperature disordered phase to the low-temperature one is of nonlinear stochastic nature. It significantly depends on the prehistory of the sample, quenching conditions and external effects. Based on the recently developed stochastic model [1], which allows to predict all stages of domain ordering, the influence of the initial disorder on the temporal evolution of the system and its physical properties was studied.

The variance D can be found by solving the system of differential equatons

$$d\pi/d\tau = \pi(1 - \alpha_z - 3D) - \pi^3 +.\varepsilon_a,$$
$$dD/d\tau = [2 - 6\pi^2 - 6D - \nu(\tau)]\, D, \qquad (1)$$

where $\pi = \langle P_z(r,\tau)\rangle/P_s$ is the dimensionless mean polarization, ε_a is determined by a voltage V applied to the electrodes, α_z is a geometrical factor.

Considering the polarization and electric field components as Gaussian random variables, the analytical expressions for time-dependent correlation length and two-point correlation function (Fig. 1) were obtained for three forms of initial disorder: Gaussian, exponential and complementary error function. We are used the following initial correlation functions:

1) the Gaussian shape $K(s,0) = K_0 \exp(-s^2/(2r_c^2))$; (2)
2) the exponential form $K(s,0) = K_0 \exp(-s/\xi)$; (3)
3) the complementary error function form $K(s,0) = K_0 erfc(s/\xi)$; (4)

The assumption of the exponential form of the initial disorder arising after quenching the sample showed the best fitting with known experiments on the cooling of uniaxial triglycine sulfate crystal. It was shown the imperfection of the Ising approach of the scalar order parameter with zero domain wall thickness for polarization correlations processing used in all known experiments. Both the correlation length and the polarization correlation function exhibited universal features independent of the applied electric field.

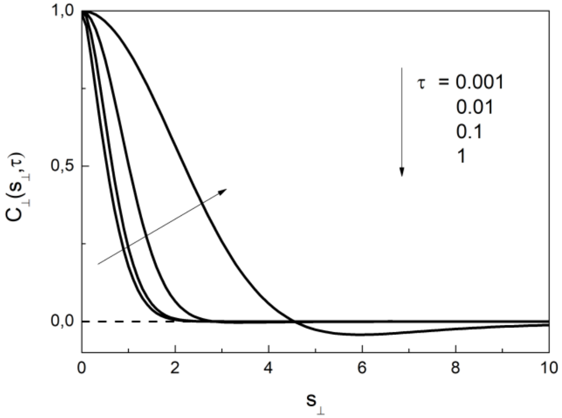

Fig. 1. The time development of spatial dependence of the correlation coefficient $C_{\perp}(\boldsymbol{s}_{\perp},\tau)$ using the parameters ξ=1, η=1 and represented for the dimensionless times τ=0.001, 0.01, 0.1 and 1.

Both the correlation length and the polarization correlation function exhibited universal features independent of the applied electric field. The impact of the initial state properties on the coercive field deciding between the single- and multidomain structure formation was disclosed. The expressions for charge density correlations allowed to theoretically describe such enigmatic results as the reduction of charge at head-to-head and tail-to-tail boundaries in such uniaxial ferroelectrics as triglycine sulfate and lead germanate.

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TRICRITICAL BEHAVIOR OF $BaTiO_3$ UPON PHASE TRANSITION

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The influence of hydrostatic pressure on the formation of the domain structure of a barium titanate ($BaTiO_3$) crystal during the phase transition was considered in order to develop innovative methods of creating stable homogeneous perovskite samples, which are in demand in photovoltaics and renewable energy sources.

Based on the phenomenological theory, a theoretical model was created and a new approach to calculate the value of the tricritical point was proposed.

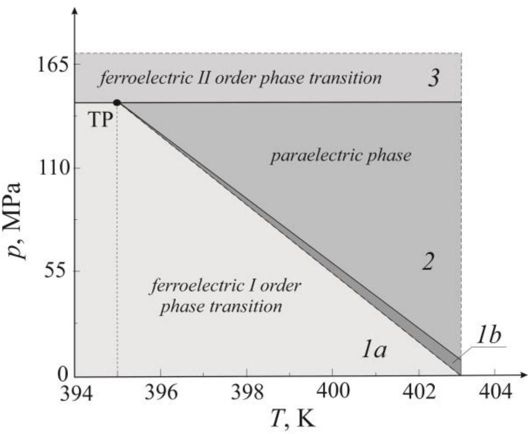

Fig. 1. Phase diagram $p - T$ with an indication of the tricritical point TP with coordinates $p = 145$ MPa, $T = 395$ *K*. In sector *1*, a first-order ferroelectric phase transition takes place: sector *1a* corresponds to the polydomain structure formation; sector *1b* corresponds to the single-domain structure formation. Sector *2* defines the region of the disordered (paraelectric) phase under pressure. Sector *3* corresponds to second-order ferroelectric phase transitions.

The obtained phase diagram allows establishing the pressure and temperature values at which single-domain, polydomain, and partially ordered structures are formed. The developed theoretical model is a very useful methodological tool for preparation and optimization of experiments. Together with our scientific partners in Japan, an experiment was carried out on differential scanning calorimetry in a wide pressure range (0.1–60 MPa). A two-stage phase transition mechanism and a nonlinear nature of the pressure-thermal hysteresis were established.

Classical methods for controlling the domain ordering process are limited by technological issues and size effects. We have proposed a new method for obtaining ferroelectric single-domain structures, which is based on the formation of domains under highly nonequilibrium conditions. This method is very promising for obtaining single-domain and regular domain structures with a submicron periodIn this paper it is shown that the initial heterogeneity of the system under certain conditions determines the nature of the evolution of the domain structure.We show that the initial inhomogeneity of the system under certain conditions determines the nature of the evolution of the domain structure.

We found that only a polydomain state is formed in a barium titanate crystal when the weak external hydrostatic pressure $p < 19$ MPa is imposed on the sample. A strong pressure $p > 19$ MPa leads to the suppression of the ferroelectric phase and the formation of a single-domain structure in systems with low and high initial inhomogeneity, respectively. We found an expansion of the range of admissible pressures for the monodomainization of the system with an increase in the value of its initial dispersion of polarization. We show that it is not necessary to use "ideal" crystals to obtain single-domain structures. The high initial inhomogeneity of the system, which depends on the quenching rate and concentration of defects, can be an auxiliary tool for controlling the domain ordering. These results will be useful in preparing experiments under highly nonequilibrium conditions, where it is difficult to maintain the temperature and pressure values. Controlling the initial inhomogeneity of the sample by the quenching rate and alloying expands the possibilities for sample monodomainization. This will improve the methods for obtaining stable single-domain structures for modern device making, including high-efficiency solar cells.

The work was supported by the IEEE "Magnetism for Ukraine 2022/2023 initiative" (STCU project #9918).

TRANSPORT PROPERTIES OF 2D CONDUCTING SYSTEMS WITH SPIN-ORBIT INTERACTION UNDER MAGNETIC FIELD DRIVEN TOPOLOGICAL TRANSITION

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In two-dimensional (2D) electronic systems with significant spin-orbit interaction, changing of the magnitude and direction of the magnetic field **B** parallel to the conducting plane, changes geometry of the Fermi contours corresponding to different spin bands. The topological Lifshitz phase transitions associated with a break in the bridge between parts of the contours, as well as the appearance or disappearance of a Fermi contour become possible. These topological transitions lead to the appearance of Van Hove singularities in the electron density of states and abruptly changes in dependence of kinetic coefficients on the in-plane magnetic field. In the case of Rashba or Dresselhaus spin-orbit coupling, the change in the Fermi contour with increasing magnetic field is shown in fig. 1. The larger contour corresponds to the lower spin zone, and the smaller one corresponds to the upper zone. When B is equal to $2\sqrt{\varepsilon_0\varepsilon_F}/\mu_0$, ($\varepsilon_0$ is the energy of the spin-orbit interaction, ε_F is the Fermi energy, μ_0 is the electron magnetic moment), a topological phase transition occurs due to a change in the connectivity of the Fermi contour, fig. 1b. At $B > (\varepsilon_0+\varepsilon_F)/\mu_0$, the minimum energy of the upper branch of the energy spectrum exceeds of the Fermi energy, i.e. only the lower spin band is filled. fig.1d.

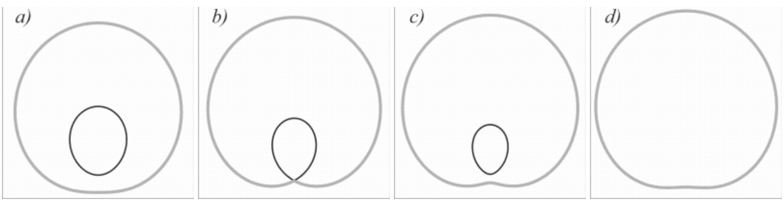

Fig. 1. Fermi contour in momentum plane in various ranges of values of B :
a) $B < 2\sqrt{\varepsilon_0\varepsilon_F}/\mu_0$, *b*) $B = 2\sqrt{\varepsilon_0\varepsilon_F}/\mu_0$, *c*) $2\sqrt{\varepsilon_0\varepsilon_F}/\mu_0 < B < (\varepsilon_0+\varepsilon_F)/\mu_0$,
d) $B > (\varepsilon_0+\varepsilon_F)/\mu_0$.

The dependences of conductivity $\sigma_{||}$ and magnetic susceptibility $\chi_{||}$ in the direction of **B** on magnetic field in the case of Rashba spin-orbit coupling, at different values of frequency ω of alternating electromagnetic field are presented in fig.2. At $B = (\varepsilon_0 + \varepsilon_F)/\mu_0$, the minimum energy of upper spin zone become equal to the Fermi energy, and the kinetic coefficients as a functions of magnetic field change in discrete step [1]. The minimums in fig. 2a correspond to the value $B = 2\sqrt{\varepsilon_0 \varepsilon_F}/\mu_0$.

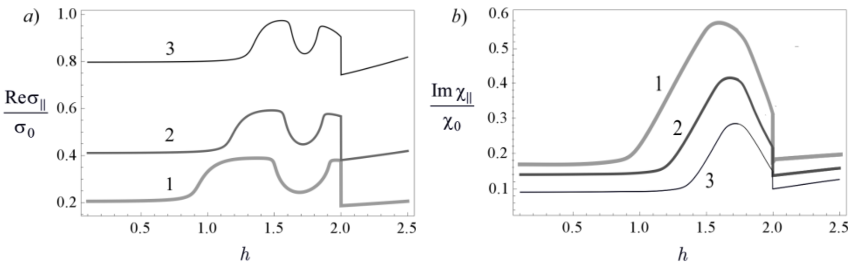

Fig. 2. The dependences of Re$\sigma_{||}$ (a) and Im$\chi_{||}$ (b) on $h = \mu_0 B/(2\varepsilon_0)$, at different value of frequency, curves 1-3 correspond to the values of the parameter $\hbar\omega/2\varepsilon_0 = 1, 0.7, 0.5$, here $\varepsilon_F/\varepsilon_0 = 3$, σ_0 and χ_0 are constants.

To observe the magnetic field driven topological transitions, it is necessary that the ratio $\varepsilon_0/\varepsilon_F$ of the spin-orbit interaction energy to the Fermi energy should not be a vanishingly small value. The more the ratio $\varepsilon_0/\varepsilon_F$ the smaller the magnetic fields are required. Consequently, the favorable condition to study the effect can be in systems with either a low electron density or strong spin-orbit interaction. Such as for the typical values of electron density $n \sim 10^{10}$cm^{-2}, spin-orbit constants $\gamma = 10^{-10}$ eV cm and Fermi energy $\varepsilon_F \sim 0.1$ meV for an Al_x Ga_{1-x} N/GaN heterostructure, topological transition may appear in a magnetic field of the order of 1T. Other possible candidates to observe the considered phenomena are the 2D conducting systems with high energy of spin-orbit interaction, for example, surface of polar semiconductor BiTeI or $LaAlO_3/SrTiO_3$ interfaces.

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NONLINEAR WAVELENGTH TRANSFORMATION AND SHORT EXCHANGE SPIN WAVES EXCITATION IN PERPENDICULARLY MAGNETIZED NANOWAVEGUIDES

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Spin waves (SWs), the collective excitations of the magnetic orders, provide a scalable wavelength and exhibit a variety of distinct nonlinear phenomena that make spin waves promising for data processing at the nanoscale [1]. To date, many spin-wave processing elements, both analog and digital as well as novel non-Boolean ones have been proposed and verified [2-3]. At the same time, several problems hinder the development of integrated spin-wave circuits. One of the crucial problem is a lack of an efficient mechanism to excite long-running exchange SWs. It should be stressed that only utilization of short nanoscale SWs allows to reach all the predicted advantages of magnonic devices in terms of operation speed and energy efficiency [3].

Here, we report a possible solution of this challenge. We study excitation of forward-volume SWs in 200 nm wide nanoscale YIG waveguides by a micron-wide microstrip antenna with microfocused Brillouin light scattering spectroscopy. Nanoscale width allows to suppress nonlinear multimagnon scattering and thus achieve a quasi-uniform magnetization precession with unprecedented precession angle of $\theta \approx 53°$ under the antenna. High amplitude of the magnetization precession shifts the SW dispersion by about 2 GHz and, in the chosen geometry of forward volume SW, this shift is positive, which is crucial point in the studied excitation mechanism.

Outside the antenna magnetization precession angle decreases leading to the transformation of SW wave number from $k \sim 0$ to $k_1 = 19.4\ \mu m^{-1}$ (SW wavelength is 323 nm). This transformation takes place just near the antenna (see inset in Fig. 1) and is not related to the dissipation as evidenced by theoretical analysis. Moreover, this itinerant nonlinear transformation is very efficient having the efficiency of more than 80%, which is impossible to achieve with linear transformation methods utilizing nonuniform bias field or magnetic energy landscape. Further reduction of SW amplitude in the course of propagation results in a final SW wavelength about 230 nm.

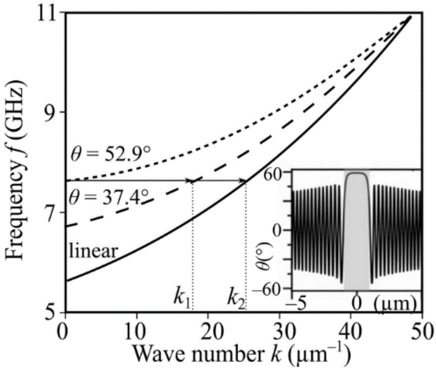

Fig. 1. Mechanism of wavelength transformation. The curves show linear (solid) and nonlinear (dashed and dotted) SW dispersions. Nonlinear quasi-uniform mode under the antenna with θ = 52.9° transforms into lower-amplitude short SW with k_1 = 19.4 μm^{-1}, which then tends to k_2 = 26.6 μm^{-1} in the course of propagation under damping-related amplitude decrease. Inset shows simulated SW profile near the 2 μm wide antenna (gray shaded area).

By means of micromagnetic simulations we show that the proposed method, if applied to metallic nanowaveguides, should allow to excite SWs down to 50 nm wavelength. In addition to efficient short SW excitation, this nonlinear mechanism provides also self-normalization of SW amplitude, which is mostly determined by the force frequency, but not the magnitude (above certain threshold). Moreover, with a minor modifications, the same nonlinear excitation mechanism allows for the realization of magnonic repeater [4] and unidirectional magnonic emitter.

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THERMALLY-INDUCED DIFFUSION AND FORMATION OF ANTIFERROMAGNETIC $L1_0$-MnPt PHASE IN Pt/Mn-BASED LAYERED STACKS

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Antiferromagnetic materials based on the binary chemically-ordered equiatomic MnPt phase are of practical relevance due to potential widespread application in advanced technologies of spintronics, particularly in spin valves for magnetic sensors and magnetic heads to pin the magnetization of ferromagnetic layers and spin–orbit torque devices. The technological relevance of MnPt-based materials is related to their high Néel temperature (700 °C), spin flop field (72 T), satisfactory corrosion resistance and compatibility with modern silicon technologies of integrated circuits [1].

In this study, we demonstrated possibility to achieve thermally-induced formation of $L1_0$-MnPt phase via annealing of layered stacks based on Pt/Mn. Moreover, we compared structural and morphological properties as well as the rate and mechanisms of diffusion processes in bi-layered Pt/Mn and tri-layered Pt/Mn/Pt stacks of the same total thickness.

Bi-layered Pt(24 nm)/Mn(20 nm)/sub. and tri-layered Pt(12 nm)/Mn(20 nm)/Pt(12 nm)/sub. stacks were fabricated using magnetron sputtering and subjected to the following annealing in vacuum of 10^{-6} mbar in the temperature range of 300 °C – 600 °C for 30 min. The phase composition and structural characteristics of the as-deposited and post-annealed stacks were analyzed at room temperature using X-ray diffraction. Chemical depth profiling of the stacks was performed using secondary ion mass spectrometry. Moreover, surface morphology of thin film samples was investigated by atomic-force microscopy.

We compared the diffusion rates of the components in bi- and tri-layered stacks taking into account several factors. It was found that the diffusion rate of Mn is significantly higher than that of Pt, being in agreement with the melting points of these metals. However, the melting point of a metal could affect not only its diffusivity but also the size of the grains formed at the deposition stage (in Mn the grain size is expected to be larger than in Pt). Furthermore, the structure of Mn layer depends on the nature of a seed layer used: in the Pt/Mn/Pt stack, the Mn film is grown on the Pt layer while in Pt/Mn it is grown directly on the amorphous silicon dioxide. Thus, the Mn film deposited directly on the substrate should have a larger grain size compared to the deposition on the Pt layer. A finer grain structure leads to a more branched grain boundary network and acceleration of the atomic diffusion via grain boundary mechanism at the initial stages of mass transfer. As a result, the intermediate Mn layer should be less defective as well as more intensively and homogeneously saturated by the Pt atoms. This fits well to the obtained structural data that revealed higher crystallinity degree and smaller grain size of the tri-layered stack. The schematic illustration of the diffusion phase formation of both investigated stacks upon annealing is shown in Fig. 1 [2].

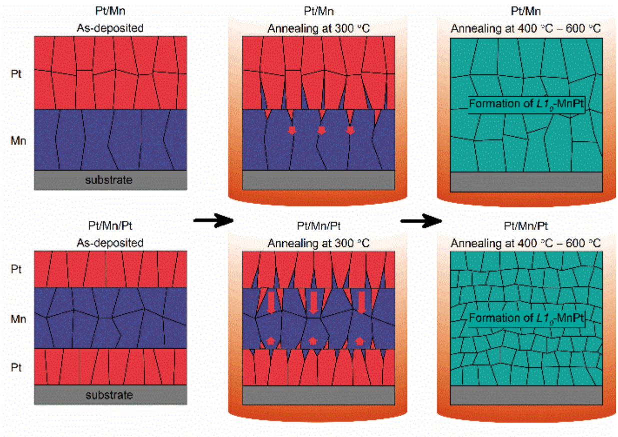

Figure 1. Schematic illustration of the thermally-induced diffusion processes and phase formation in Pt/Mn and Pt/Mn/Pt layered stacks.

The work was supported by the IEEE "Magnetism for Ukraine 2022/2023 initiative" (STCU project #9918), project entitled "Diffusion formation of MnPt-based $L1_0$-ordered antiferromagnetic thin films".

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OPTICAL AND MAGNETIC PROPERTIES OF Mn-DOPED DILUTED MULTICOMPONENT SEMICONDUCTOR EPITAXIAL LAYERS

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Dilute multicomponent semiconductors represent a unique class of alloys that integrate semiconducting properties with either ferromagnetism or superconductivity. This combination yields intriguing physical characteristics with potential applications in both fundamental research and practical device design. By introducing doping ions such as P, In, or Bi into a III-V semiconductor matrix [1–3], it is possible to tailor the band structure and explore innovative device concepts.

In this study, we provide a comprehensive investigation of the physical properties of dilute multicomponent III-V semiconductor nanofilms. Our approach employs a range of analytical techniques, including Fourier-transform infrared spectroscopy, spectroscopic ellipsometry (SE), high-resolution X-ray diffraction (HRXRD), micro-Raman spectroscopy, and SQUID magnetometry. These techniques enable the precise determination of the material's magnetic and optical properties, including dielectric functions, band structure, Curie temperature, easy magnetization axes and planes, and other key characteristics. This detailed understanding is essential to fully realize the potential of ultra-thin III-Mn-V semiconductors and topological semimetals for magnetic storage and microwave technology applications [4,5].

Our primary focus is on quaternary (Ga,Mn)(BiAs), (Ga,Mn)(P,As) compounds with varying concentrations of Bi (up to 1%), P (up to 32%), and Mn (up to 8%), along with $NiMnTe_2$ layers containing Mn up to 1%, grown by molecular beam epitaxy (MBE) on p-type, n-type, and semi-insulating (001) GaAs substrates. We measured the absorption infrared spectrum using a Nicolet 380 spectrometer (Thermo Fisher Scientific), covering a broad range from 400 to 4000 cm^{-1}, and complemented these measurements with SE-2000 Semilab multi-angle spectroscopic ellipsometer data (wavelength range: 250–2100 nm).
The HRXRD confirmed the crystalline quality of the layers and sharp interfaces with the GaAs substrate, revealing the pseudomorphic growth of all nanofilms on (001) GaAs. SQUID magnetometry measurements confirmed the

ferromagnetic nature of (Ga,Mn)As and (Ga,Mn)(Bi,As) layers at low temperatures, showing easy-plane magnetic anisotropy—a characteristic observed in (Ga,Mn)As layers grown under compressive misfit strain. Magnetization curves at 5 K revealed that the in-plane ⟨100⟩ directions serve as easy magnetization axes in both systems. Notably, tensile-strained (Ga,Mn)(P,As) films grown on GaAs with P doping exhibit ferromagnetism with perpendicular magnetic anisotropy, making them ideal for observing the anomalous Hall effect. Co-doping Mn with either Bi or P allows independent tuning of the magnetic and electrical properties of these systems. The (Ga,Mn)(Bi,As) and (Ga,Mn)(P,As) materials combine the characteristics of (Ga,Mn)As with those of Ga(Bi,As) and Ga(P,As) ternary compounds, offering the potential to tailor the bandgap structure to suit novel device functionalities in future spintronic and photonic applications.

Introducing Mn ions results in a prominent plasmon-phonon peak in the Raman spectrum and enhances sub-band edge absorption across all epitaxial layers. Bi doping significantly increases the spin–orbit splitting energy due to a substantial relativistic correction in the valence band structure from the heavy Bi atoms. Additionally, Bi doping appears to reduce the deviation of the spin–orbit split-off band dispersion from the tight-binding approximation. The band edge shape aligns with an impurity band model, indicating a significant modification of the valence band dispersion near the edge.

Incorporating P ions into the GaAs crystal lattice increases the bandgap, while Mn doping decreases it. Mn impurities also impact the structural and magnetic properties of the films, enhancing the charge density and optical gap. Our findings suggest the presence of Mn in-gap impurity states, contrasting with the Fermi level blue-shift observed in (Ga,Mn)As, (In,Ga,Mn)As, and (Ga,Mn)(Bi,As) epitaxial layers, attributed to the Moss-Burstein effect.

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