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National Research Foundation of Korea Belarusian State University

Joint Belarus-Korea Symposium on the Physics of Functional Nanomaterials and Nanodevices

Program & Book of Abstracts

Research Institute for Nuclear Problems

Faculty of Physics, BSU

June 17-19, 2014

Minsk, 2014

Joint Belarus-Korea Symposium on the Physics of Functional Nanomaterials and Nanodevices

June 17-19, 2014

The Symposium is organized in the framework of an agreement on scientific and technical cooperation between the National Research Foundation of Korea and the Belarusian Republican Foundation for Fundamental Research. The Symposium has been granted by the National Research foundation of Korea.

The purpose of the Symposium is exchange of experience and establishing contacts between scientific communities of Belarus and Korea in the field of functional nanomaterials and nanodevices.

The Belarusian scientists and scientists from Korean universities: Hanyang University, Ewha Womans University, Dongguk University, Konkuk University, will attend the Symposium.

Research and teaching staff, Ph. D., graduate and undergraduate students are invited to participate in the event.

Organizing Committee:

Jin Pyo Hong, Department of Physics, Hanyang University, Seoul, Korea (Co-chair)

V.M. Anishchik, Faculty of Physics, BSU (Co-chair)

S.A. Maksimenko, Research Institute for Nuclear Problems, BSU (Co-chair)

S.N. Sytova, Scientific Secretary of INP BSU (Secretary), sytova@inp.bsu.by

Seung-Woong Lee, Dept. of Semiconductor Science, Dongguk Univ. Seoul, Korea

V.K. Ksenevich, Laboratory of Electronic Materials Research, Faculty of Physics, BSU

The official language is English.

Full information is on site http://inp.bsu.by/Korea2014/index.htm.

Program

17 June, 12:00 Meeting in the Rector's office

Lunch

17 June, BSU Faculty of Physics, auditorium 330

Opening *15:00-15:10*

Session I: 15:10-16:30.

1. Jin Pyo Hong. Binary oxide-based resistive switches in configurations for 3D nano-scalable stackable nonvolatile memory applications
2. G.E. Malashkevich, V.V. Kouhar, T.G. Khottchenkova, V.A. Orlovich, I.A. Khodasevich. Optical materials on the basis of CeO_2:Ln and Yb_2O_3:Ln nanoparticles: synthesis, structure and spectral-luminescent properties
3. Seokhyun Yoon. Raman Scattering Studies of Various Condensed Matter Systems
4. V. Baryshevsky, N. Belous, A. Gurinovich, E. Gurnevich, P. Kuzhir, S. Maksimenko, P. Molchanov, M. Shuba, T. Kaplas, Yu. Svirko. Study of nanometrically thin pyrolytic carbon films for explosive electron emission cathode in high-voltage planar diode

Coffee break 16:30 - 16:50

Session II: 16:50-18:30

5. Dong-Wook Kim. Efficient Management of Photons and Carriers using Metal and Semiconductor Nanostructures for Novel Photovoltaics
6. J. Fedotova, A. Fedotov, I. Svito, P. Zukowski, T. Koltunowich. Development of microminiature planar (noncoil-like) inductive elements based on metal-semiconductor-dielectric nanocomposites
7. A. Kukhta. Organic-inorganic Nanocomposites for Electrode Applications
8. V. Lapanik, A. Lugouskiy. Influence of the size and the attached organic tail of modified diamond nanoparticles on the physical properties of liquid crystals

Welcome party 18:40 - 22:00

18 June, BSU Faculty of Physics, auditorium 330

Session III: 9:30-10:50.

9. V. E. Borisenko. Resistivity switching in hafnium dioxide nanostructures
10. Jinki Hong, Jin Dong Song, Joonyeon Chang. Magneto-diode: principle and application to chameleon processor
11. A.Antanovich, A. Prudnikau, A. Fedosyuk, M. Artemyev. Thin Film Structures from Semiconductor Heteronanocrystals Optics and Optoelectronic Applications

12. J. Fedotova, A. Fedotov, A. Mazanik, I. Svito, E. Streltsov. A huge magnetoresistive effect in n-Si/SiO_2/Ni nanostructures fabricated by the template-assisted electrochemical deposition

Coffee break 10:50 -11:20

Session IV: 11:20-13:00

13. Hyunsik Im, Hyunsang Kim, Jongmin Kim, Yongcheol Jo, J. Han. Electrochemical Characteristics of flexible supercapacitors with PANI-MWCNT/graphene nanocomposite electrodes
14. N. A. Poklonski. Carbon low-dimensional systems in electromechanics
15. Seung-Woong Lee, Won Chel Choi. Growth of carbon nanotubes with diameter and density control
16. S. A. Maksimenko, M.V. Shuba, P. P. Kuzhir. Terahertz response of length-calibrated carbon nanotube thin films
17. V. K. Ksenevich. Charge transport in arrays of carbon nanotubes

Lunch 13:00 - 15:00

Session V: 15:00-16:40

18. Hyunsang Kim, Hyunsik Im, Jongmin Kim, Yongcheol Jo, J. Han. Effects of atomically engine-ered junction interface on resistive switching performance in Al-WO_x-Al resistive memory
19. V.V. Uglov, S.V. Zlotski, A.Y. Rovbut. Ion irradiation behavior of nanostructured TiZrAlN-based hard coatings'
20. D.B. Migas, A.B. Filonov, V. E. Borisenko. Orientation effects in structural and electronic properties of anatase TiO_2 nanowires and nanotubes
21. V. Lapanik, A.Lugouski, S.Timofeev. Special Nanoparticles as a Basis to Create Fast-Switching VA LCD's with Wide Viewing Angle
22. E. A. Streltsov, N. V. Malashchonak, A. V. Mazanik. Synthesis and characterization of nanohetero-structures based on wide-gap oxides and nanoparticles of chalcogenide semiconductors
23. M.V. Shuba, A.G. Paddubskaya, P. P. Kuzhir, S.A. Maksimenko. Microwave spectroscopy of single-walled carbon nanotube suspension: theory and experiment

Coffee break 16:40 -17:10

Session VI: 17:10-18:00

Roundtable discussion

Closing Session

Binary oxide-based resistive switches in configurations for 3D nano-scalable stackable nonvolatile memory applications

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Resistive switching (CRS) behaviors are systematically analyzed with various TiO_x based multi-layers. Each TiO_x layer was intentionally prepared to have different oxygen contents for oxygen ion rich-region and oxygen ion poor-region. At first, the basic framework is the two bipolar home junctions of TiO_x/TiO_y and TiO_y/TiO_x and then two homo-junctions are anti-serially merged without using any additionally middle electrode. Unique I-V phenomena are clearly observed. The nature of the resistive switching behaviors in each structure may be related to the redox reactions at the interfaces induced by the migration of oxygen ion under external bias.

Optical materials on the basis of CeO_2:Ln and Yb_2O_3:Ln nanoparticles: synthesis, structure and spectral-luminescent properties

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Silica glasses, siliceous powders, films and glass ceramics on the basis of CeO_2:Ln and Yb_2O_3:Ln nanoparticles have been synthesized with the help of the sol-gel process. These materials structural and optical properties were investigated with the use of X-ray diffraction, scanning electron microscopy and spectral-luminescent methods.

It is shown that main features of Ln^{3+} ions (Ln ≠ Ce) in the CeO_2 nanoparticles are a high relative intensity of magnetic dipole transitions, a weak vibronic interaction with the matrix and sufficiently effective sensitization of their luminescence with labile photoreduced Ce^{3+} ions by means of superexchange mechanism or/and by transfer of electron. At reduction of Ce^{4+} ions with hydrogen in the nanoparticles to Ce^{3+} ones without a destruction of the Ce–O–Ln bond configuration, the Ln^{3+} ions spectral-luminescent characteristics may dramatic change however an efficiency of their luminescence sensitization by the stable Ce^{3+} ions may approach to 100%. An influence of some extrinsic local charge compensators on structural and spectral-luminescent properties of the materials is considered.-

A main feature of materials on the basis of the Yb_2O_3 nanoparticles is an effective cooperative luminescence of Yb^{3+} pairs in addition to the basic $^2F_{5/2} \rightarrow {}^2F_{7/2}$ band. At substitution of Yb^{3+} ions in the nanoparticles with Eu^{3+} and Er^{3+} ones and excitation in the $^2F_{7/2} \rightarrow {}^2F_{5/2}$ band, an intense anti-Stokes luminescence of the substituents from the corresponding levels is appeared due to the transfer of excitation from Yb^{3+} ions and their pairs. On the contrary, the anti-Stokes luminescence of Ho^{3+} in the Yb_2O_3:Ho nanoparticles is very low-intensive. The main reason of this effect is the back excitations transfer according to the $Ho^{3+}(^5F_4 \rightarrow {}^5I_6)$–$Yb^{3+}(^2F_{7/2} \rightarrow {}^2F_{5/2})$ scheme. It is necessary to draw attention to the high "spectroscopic potential" of the Yb_2O_3:Ln nanoparticles. In particular, at doping of their containing media with some additives they can show an intense anti-Stokes luminescence which may be ascribed to some new molecules rather than individual rare-earth ions, see Fig. 1. Some applications of the described materials as laser media and anti-Stokes luminophors are discussed.

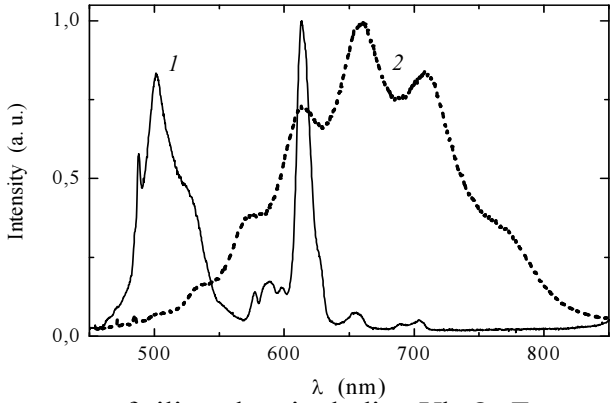

Fig. 1. Anti-Stokes luminescence of silica glass including Yb_2O_3:Eu nanoparticles (*1*) without and (*2*) with additive.

Session I:3

Raman Scattering Studies of Various Condensed Matter Systems

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Optical spectroscopic techniques such as Fourier Transform InfraRed (FTIR), ellipsometry, or Raman scattering spectroscopy are applied to diverse areas such as astronomical observation, characteristics of semiconductor device materials, monitoring phase transition behavior, quantum effects in low-dimensional materials, etc, and give us important scientific information. These techniques are still widely used in various disciplines including academia and industries despite the fact that they are rather old techniques that has been developed for about 100 years. In this presentation, basics of several optical spectroscopies, especially Raman scattering spectroscopy will be briefly reviewed and spectroscopic research activities in condensed matter systems including various oxides, semiconductor device materials, thin films for solar cells, low dimensional nanostructured materials, etc. will be introduced. Recent application of Raman scattering to nanometer-scale spectroscopy, i.e., SERS (surface enhanced Raman scattering) and TERS (tip enhanced Raman scattering) will be briefly introduced as well.

Study of nanometrically thin pyrolytic carbon films for explosive electron emission cathode in high-voltage planar diode

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We report high current density explosive electron emission from a copper cathode with diameter of 50 mm with pre-deposited pyrolytic carbon (PyC) films being from 70 to 150 nm thick. In the diode configuration, we demonstrate the current density as high as 300A/cm2 under applied voltage below 400 kV. The Raman measurements reveal that the PyC film survives after 7 shots. In order to study the cathode degradation we compared optical microscope images of the cathode before and after shots. We observed that the pre-deposited PyC film cathode prevents copper evaporation and oxidation. This property ensures a higher explosion emission stability and longer lifetime of the PyC/Cu-cathodes in comparison with conventional graphitic/Cu ones. Our results show that PyC/Cu cathodes are most promising for applications that require electric field strengths from 50 to 60 kV/cm.

Efficient Management of Photons and Carriers using Metal and Semiconductor Nanostructures for Novel Photovoltaics

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Crystalline Si solar cells currently dominate the photovoltaic (PV) industry. The cost burden of Si wafers accounts for 40% of the module cost, retarding the mass deployment of Si PV devices. Thus, use of ultrathin absorber has surfaced as a critical issue to realize high-efficiency and low-cost c-Si solar cells. Thinner Si absorber has seriously lower optical absorption, due to the indirect bandgap, and hence there have been intensive efforts to enlarge optical thickness of Si. Resonant/guided optical mode excitation and plasmonic effects have been suggested as new approaches in addition to traditional light trapping strategies, including surface texturing and antireflection coating. In nanostructures, it is often large surface-to-volume ratio often causes carrier recombination and resulting electrical loss. Therefore we need to find device architectures maximizing both absorption of incident light and collection efficiency of the photogenerated carriers.

In this talk, I will present experimental and simulation studies of solar cells with micro-/nano-scale patterns of Si absorber, transparent conducting oxides, and metal contacts. The nanostructures exhibit enhanced optical absorption in broad wavelength range, compared with the planar counterparts. Finite-difference time-domain (FDTD) simulations clearly revealed that the patterns concentrate the optical field near the surface with the help of the resonant guided mode formation, the Fabry-Perot interference, and the antireflection effect due to the graded refractive indices. The concentration of light near the surface enables very efficient carrier collection, well supported by the experimental quantum efficiency data. All these results suggest that the patterned absorbers can provide a very promising way to realize high-efficiency and low-cost Si solar cells.

References

1. H. H. Park *et al*., *Opt. Express* **22**, A723 (2014).
2. X. M. Xu *et al*., ACS Nano **8**, 885 (2014).
3. J. Kim *et al*., *Opt. Express* **21**, A607 (2013).
4. H. Kim *et al*., *Appl. Phys. Lett.* **102**, 193904 (2013).
5. J. Kim *et al*., *Appl. Phys. Lett.* **101**, 143904 (2012).
6. E. Lee *et al*., *Solar Energy Mater. Solar Cells* **103**, 93 (2012).

Development of microminiature planar (noncoil-like) inductive elements based on metal-semiconductor-dielectric nanocomposites

J. Fedotova[1], A. Fedotov[2], I. Svito[2], P. Zukowski[3], T. Koltunowich[3]

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In the last two decades much attention was paid to the creation of nanomaterials, and nano- and microstructures on their base, exhibiting the so-called "negative capacitance" (NC) effect that is equivalent to the prevailing of inductive contribution to their impedance. More recent studies were conducted with the thin-film granular nanocomposite materials containing FeCo-based ferromagnetic nanoparticles (with sizes 1-20 nm) in dielectric matrixes (alumina, PZT, calcium fluoride, silica). They have demonstrated that equivalent circuits for some types of these composites involve additionally the inductive component as well [1, 2].

It was shown that NC effect is enhanced in $(FeCoZr)_x(Al_2O_3)_{1-x}$, $(FeCoZr)_x(PZT)_{1-x}$ and $(FeCoZr)_x(CaF_2)_{1-x}$ composite films deposited in argon-oxygen mixture due to the formation of FeCo-based oxide "shells" around the metallic nanoparticles. It was experimentally proved that such "core-shell" nanogranular film composites possess (at the determined metal-to-dielectric ratios) high values of specific "effective inductance" up to 20 · H/· m^3 both after post-synthesis annealing (for composites FeCoZr-Al_2O_3) and just after ion-beam synthesis (for composites FeCoZr-PZT and FeCoZr-CaF_2). So, the key moment for getting high values of specific "effective inductance" consists of the formation of FeCo-based nanoparticles with the structure "core-shell", embedded into dielectric matrix. In so doing, metallic FeCo-based "core" is surrounded by native FeCo-oxides having semiconducting properties. Only such nanostructures show NC (inductive-like) effect.

To explain this effect we developed a special theoretical model of hopping carrier transport between nanoparticles under subjection of weak alternating electric field. The model takes into account the strong polarization of dielectric matrix, surrounding charged nanoparticles, resulting the dipole formation. The latter results in the delay of electrons on nanoparticles resulting in the positive angle of phase shift between current and voltage applied that is equivalent to the appearance (prevailing) of inductive-like impedance ("negative capacitance").

References

1. T.N. Koltunowicz, P. Zukowski, M. Milosavljević, J.V. Kasiuk, J.A.Fedotova, Yu.E.Kalinin, A.K. Fedotov. AC/DC conductance in granular nanocomposite films $(Fe_{45}Co_{45}Zr_{10})_x(CaF_2)_{100-x}$, *J.Alloys Compds*. (2012) doi:10.1016/j.jallcom.2012.09.121.

2. T.N. Kołtunowicz, J. Fedotova, P. Zhukowski, A. Saad, A. Fedotov, J. V. Kasiuk, A.V. Larkin. Negative capacitance in (FeCoZr)–(PZT) nanocomposite films, *J. Phys. D: Appl. Phys.* 46 (2013) 125304.

Organic-inorganic Nanocomposites for Electrode Applications

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Thin film flexible electrodes for printing technologies are attractive for manifold applications in electronic devices during the last decade. Transparent electrodes conduct electrical current and allow light to pass through. Such electrodes are required for photo-voltaic, electroluminescent devices, touch screens etc. Electrodes with high surface area are developed for supercapacitors and dye sensitized solar cells. Conducting polymers, metal colloids, and carbon nanomaterials are used for the development of printable and flexible electrodes. The ideal electrode can be made from graphene. However, this process is expensive. One of the possible roots for the creation of printable flexible electrodes is based on organic-inorganic nanocomposites.

In this talk our achievements on the creation approaches and physical properties of nanocomposites based on conducting polymer or other organics material and metal nanoparticles or carbon nanomaterials, partially graphene are presented. We showed that the replacing of aliphatic shell of metal nanoparticles with aromatic one in polymer-metal nanocomposite, and application of triple nanocomposite results in conductivity increase without transparency loosing. Good results are obtained with graphene-metal nanoparticles nanocomposite.

References

1. A.V.Kukhta, E.E.Kolesnik, I.N.Kukhta, A.E.Pochtenny, A.V.Misevich, A.I.Lesnikovich, I.A.Milevich, E.M. Semenova, S.A.Vorobyova, E.Sarantopoulou. Optical properties and electric conductivity of nanocomposites consisting of PEDOT:PSS and gold/silver nanoparticles. Physics of Solid State 56 (2014) 827-834.

2. A.V. Kukhta, E.E. Kolesnik, A.I. Lesnikovich, M.N. Nichik, A.N. Kudlash, S.A. Vorobyova. Organic-inorganic nanocomposites: optical and electrophysical properties. Synth. & Reactivity Inorg. Metal-Org. Nano-Metal Chem. 37 (2007) 333-339.

Influence of the size and the attached organic tail of modified diamond nanoparticles on the physical properties of liquid crystals

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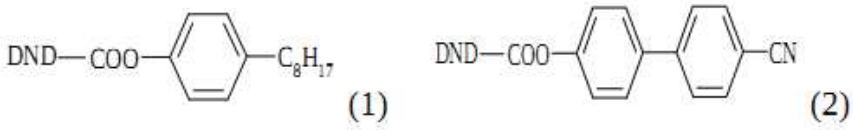
A lot of different kind of nanoparticles have been prepared and investigated during recent years. Diamond is one of the most popular materials which can exist in the form of nanoscale particles too. Special class of nanodiamond material with characteristic sizes of 4 to 5 nm, often called in the literature “ultradispersed diamond” (UDD) or “detonation nanodiamond” (DND), were produced by detonation of carbon-containing explosives [1]. The resulting conglomerates formed by nanoparticles ranged from 50 to 100 nm. Three major steps in the conversion of carbon-containing explosives to modern DND products include synthesis, postsynthesis processing, and modification.

For functionalization of DND, we attached via grafting a carboxylate group leading to only one carboxylate group at 5000-6000 carbon units. Via ozonolysis carbon atoms at the surface of the DND could be transferred in different steps to further carboxylate groups resulting in an increase of those by a factor 2-3. Activation of-COOH surface functional groups allowed the attachment of different organic tails as can be seen below:



Dielectric and electro-optical properties of nematic liquid crystalline mixtures (LCMs) doped with diamond nanoparticles have been investigated. It is established that the effect of DND on the dielectric properties depends on the size of nanoparticles and type of tails like organic molecules. It was found that nanoparticles of small size 4 to 5 nm do not significantly affect on the parameters of LCMs. At the same time, the conglomerates on the basis of nanoparticles (50-100 nm) depending on the polarity of the tails could increase or decrease the dielectric anisotropy (see Fig.1) and the response time of LCMs by 20-30%. Mixture NLC-1 contains varying amounts of nanoparticles 1 and mixture NLC-2 contains varying amounts of nanoparticles 2.

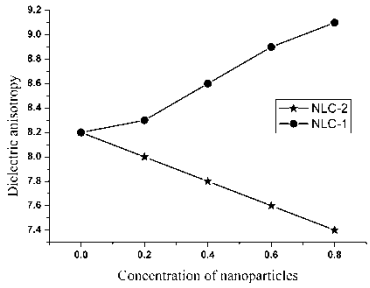


Fig.1. Dependence of the dielectric anisotropy of LCMs on the concentration and type of DND.

References

1. O.A. Shenderova, V.V. Zhirnov and D.W.Brenner, Carbon nanostructures, *Crit. Rev. Solid State Mater. Sci.*, 27, 227 (2002).

Resistivity Switching In Hafnium Dioxide Nanostructures

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An origin and peculiarities of resistivity switching in nanodevices designed as a hafnium dioxide (HfO_2) nanolayer incorporated between conducting metal or silicon electrodes are considered. Atomic structure changes, thermal reversible breakdown and charge carrier traps are discussed to form conductive nanofilaments in HfO_2 under its reversible electrical breakdown. The formation and rupture of the nanofilaments result in up to three orders of magnitude change in the current flowing through the insulator during the switching event.

The model of atomic structure changes supposes that oxygen vacancies and foreign atoms from the electrodes form conductive nanofilaments in HfO_2 under its reversible electrical breakdown. It is confirmed by *ab initio* atomic structure simulation explaining recent *in situ* transmission electron microcopy observations.

The proposed "thermal" model is based on an assumption that the thermal reversible breakdown of the insulator is due to its Joule heating displaying an exponential dependence of conductivity on temperature. The temperature and corresponding current-voltage characteristics of conductive filaments have been calculated starting with the heat conduction equation with boundary conditions accounting for the heat dissipation via electrodes. These characteristics are found to be affected by the ambient temperature and nanostructure parameters.

The traps assisted model includes a capture of charge carriers in HfO_2 followed by their ionization via a multiphonon transition mechanism. The multiphonon transitions via the Poole-Frenkel effect or electron tunneling as well as a multiphonon tunneling ionization of neutral traps have been analyzed. The proposed models are concluded to be useful for understanding atomic and electrical phenomena in resistivity switching HfO_2 based nanostructures, which are promising candidates for nonvolatile data storage and reconfiguration electronic applications.

Magneto-diode: principle and application to chameleon processor

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Chameleon processor provides novel functions such as programmable logic operation and non-volatile built-in memory. We introduce a new semiconductor magneto-electronic device that could be a good candidate of chameleon process [1]. It can offer excellent fan-out if combined with low power spintronic devices. Operation of our modified avalanche diode is based on magnetoconductance that depends on Lorentz force deflection of carriers in a magnetic field and subsequent recombination. The device can be characterized as a current switch with ON and OFF states. In this talk, we describe our prototype devices, which have demonstrated magnetoconductance ratios of more than 500% in a magnetic field of 1,000 Oe. We then discuss feasibility for integrated avalanche diode logic devices in which the magnetic field is provided by the local fringe field of a patterned ferromagnetic film with nanometer dimensions. We provide estimates of the characteristics of a model cell scaled to a feature size of about 100 nm and predict that an appropriately designed cell will have current gain.

References

1.S. Joo, et al. Nature 494, 72 (2013)

Thin Film Structures from Semiconductor Heteronanocrystals Optics and Optoelectronic Applications

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Semiconductor nanocrystals prepared via colloidal chemistry route are popular objects for studying basic properties of quantum-confined semiconductor nanostructures. Colloidal nanocrystals are also important materials for various practical applications, including optically active, electro-optic, luminescence, photovoltaic structures. Here, we discuss the recent results in the preparation and basic optical properties of semiconductor heteronanocrystals, including quantum dots, nanorods and nanoplatelets. We demonstrate the new type of “core-wings” CdSe and Type II CdSe-CdTe heteronanoplatelets have conjugate electron sub-systems important for efficient light harvesting and photogenerated charge separation and extraction in photovoltaic structures. Additionally, CdSe nanoplatelets show extra-large electro-optic response among all types of CdSe nanocrystals (dots, rods, nanoplatelets) which makes them perspective for electro-optic elements for lasers and telecommunication. Doped semiconductor heteronanocrystals are perspective materials for thin film scintillators for X-ray, high energy particles and electron beams. Highly luminescent water-soluble semiconductor quantum dost and nanorods are perspective materials for early-time supersensitive fluorescence immunoanalysis of cancer, bacterial and viral deceases. They can be used alone as fluorescent markers conjugated with different antibodies, or in composition with magnetic and plasmonic nanoparticles for magnetic separation and photothermal and magnetothermal threatment.

A huge magnetoresistive effect in n-Si/SiO_2/Ni nanostructures fabricated by the template-assisted electrochemical deposition

J. Fedotova[1], A. Fedotov[2], A. Mazanik[2], I. Svito[2], E. Streltsov[2]

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In this work we study the carrier transport and magnetotransport properties in the bundles of Ni nanorods embedded into the n-Si/SiO_2 porous template created by selective etching of swift heavy ion tracks in a SiO_2 layer when the pores are filled with nickel nanoparticles. The study of the carrier transport and magnetotransport in such nanostructures was performed over the temperature range 2 – 300 K and at the magnetic field induction up to 8 T.

As our study have shown, the n-Si/SiO_2/Ni nanostructures, being electrically similar to two Si/Ni Schottky diodes switched-on opposite to each other, display 3 contributions to the temperature dependences of equilibrium DC resistance: the zone-like carrier transport by Si substrate (at $T > 250$ K); impurity conductance by the phosphorus-doped Si substrate (at $15\ \text{K} < T < 180\ \text{K}$) when the zone-zone carrier transport by Si wafer is freezed-out; and hopping conductance by the localized states at $T < 15$ K when electrons become to move along the n-Si/SiO_2 interface over the electrons-enriched layer due to the band bending.

In n-Si/SiO_2/Ni nanostructures at the temperatures ranging 17 – 27 K, where impurity conductance by the phosphorus-doped Si substrate is predominant, a considerable positive contribution to the MR effect is observed, that may be attributed to two possible reasons - the influence of Si/Ni Schottky barriers and/or movement of electrons along the electrons-enriched Si/SiO_2 interfacial channel.

Electrochemical characteristics of flexible supercapacitors with PANI-MWCNT/graphene nanocomposite electrodes

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In this study, PANI/MWCNT nanocomposite thin films were synthesized on flexible graphene/ITO substrates for flexible supercapactior applications. The agglomerated nanoscale-vermicular-like structure of the pure PANI is converted into more uniform vermicular morphology using 12mg of MWCNT. The current density of the PANI/MWCNT/Graphene nanocomposite film obtained from the cyclic voltammogram (CV) is much stable than that without the graphene interfacial layer. The cycling stability of the nanocomposites electrode on graphene (capacitance loss: 4.87%) is significantly enhanced compared to that without the graphene layer (capacitance loss: 18.16%).

Carbon low-dimensional systems in electromechanics

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Below presented a brief review of the works performed recently at Department of Semiconductors Physics and Nanoelectronics of Belarusian State University.

A motion of a conduction electron in a quasi-one-dimensional wire placed into a dielectric environment with distributed inductance was considered. A possibility of the existence in the wire of an inductive soliton (or *inducton*) was shown and its parameters was estimated. It was found that the waveform of inducton current is compressed with an increase of inductance 11[1].

Structural and energy characteristics of the endofullerene Fe@C_{20} using density functional theory approach were calculated. The ground state of Fe@C_{20} was found to be the septet state, and the magnetic moment of Fe@C_{20} was estimated to be $8\mu_B$. The characteristics of the (8, 8) nanotube with single Fe@C_{20} inside were studied in the framework of the semiempirical approach. The scheme of magnetic nanorelay based on cantilevered nanotubes filled with magnetic endofullerenes was elaborated. The proposed nanorelay is closed as a result of bending of the nanotubes by a magnetic force. The operational characteristics of the nanorelay based on the (8, 8) and (16, 16) nanotubes fully filled with Fe@C_{20} were calculated 22[2].

Quantum-chemical semi-empirical molecular-orbital calculations of *zigzag* graphene nanoribbons (*n*zGNRs) were performed for the number of *zigzag* carbon chains $n = 4$ and 10. The antiferromagnetic (AFM) nature of zGNRs' ground state was confirmed. The energy difference between AFM and ferromagnetic (FM) states was calculated and dimerization patterns of their chemical bond lengths were elucidated. The electron energy band structure calculations show that narrow nanoribbon (4zGNR) is semiconducting in both AFM and FM states. For wider nanoribbon (10zGNR), the AFM state is semiconducting ($\approx$0.1 eV band gap), whereas the FM state is half-metallic (electrical conduction with only one spin orientation) 33[3].

We considered a possibility to fabricate a generator of alternate current on the base of a graphene nanoribbon. Contrary to the works, where field emission occurs from the butt end of the nanowire (bunch of carbon nanotubes), we proposed a more simple and production-friendly construction in the form of a double-clamped graphene nanoribbon cathode placed above the flat anode surface 44[4].

References

1. N.A. Poklonski, A.T. Vlassov, S.A. Vyrko, E.F. Kislyakov, S.V. Ratkevich, A.I. Siahlo. Physics, Chemistry and Applications of Nanostructures. Reviews and Short Notes: Proc. of the Int. Conf. Nanomeeting-2013, Minsk, 28–31 May 2013 / Eds. V.E. Borisenko [et al.] (Singapore: World Scientific, 2013) P. 36–39.
2. N.A. Poklonski, E.F. Kislyakov, S.A. Vyrko, N.N. Hieu, O.N. Bubel', A.I. Siahlo, I.V. Lebedeva, A.A. Knizhnik, A.M. Popov, Yu.E. Lozovik. J. Nanophotonics, 4, 041675 (2010).
3. N.A. Poklonski, E.F. Kislyakov, S.A. Vyrko, O.N. Bubel', S.V. Ratkevich. J. Nanophotonics, 6, 061712 (2012).
4. N.A. Poklonski, E.F. Kislyakov, S.A. Vyrko. Electromechanical vibrator based on graphene // Proc. Int. Sci. Conf. Shell and Membrane Theories in Mechanics and Biology: from Macro- to Nanoscale Structures, September 16–20, 2013, Minsk / Eds. G.I. Mikhasev, H. Altenbach (Minsk, BSU, 2013) P. 105–108.

Growth of carbon nanotubes with diameter and density control

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Controlling the diameter and density of carbon nanotubes (CNTs) has been emerging as a challenge in order to apply field emission devices. Therefore, many research groups have suggested a variety of ways to control the diameter and density.

In this work, we proposed and applied embedded catalyst method instead of conventional laminated catalyst method in order to control the diameter and density of CNTs more precisely and effectively. This method enables not only reducing one process step but also controlling density and diameter of CNTs by adjusting amount of catalyst metal in the sputtering target and adjusting rf power during sputtering process.

The density and diameter of the CNTs could be successfully controlled by the concentration of Fe in the sputter target and the rf power during the sputtering process, respectively. The density of CNTs increased with an increase in the concentration Fe in the sputter target, and the diameter of CNTs was decreased with a decrease in the rf power during the deposition of catalyst-embedded supporting layer. Furthermore, the embedded catalyst system effectively restricted the agglomeration of the catalyst, which leads to the growth of CNTs with a narrow diameter distribution, compared to the laminated catalyst system with a supporting layer.

Terahertz response of length-calibrated carbon nanotube thin films

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Thin carbon nanotube (CNT) films have attractive electronic and optical properties motivating their wide application as e.g. transparent flexible electrodes and polarizes. Optical properties of CNT films can give us information about electronic transport in nanotube at high frequencies. Especially it is important in terahertz range where the response from individual tube is very small and cannot be detected. Far infrared and terahertz conductivity of SWCNT film demonstrate non-Drude behavior. It have been reported since 1997, the conductivity spectra of SWCNT film in THz and FIR ranges can be described by imposing some resonant term over the Drude conductivity law.

Electromagnetic scattering theory is applied to calculate polarizabilities of finite-length single- and multi -walled carbon nanotubes (SW- and MWCNTs) in terahertz and IR ranges. The influence of the length and diameter of a MWCNT and electron relaxation time on the regime of the CNT interaction with an electromagnetic field is analyzed. We demonstrate theoretically the dominant role of finite size effect in the non-Drude conductivity of CNT films due to the strong slowing down of surface polariton in CNT [1,2]. Significant screening effect is demonstrated to be inherent to electromagnetic response of MWCNTs films at gigahertz frequencies while it practically disappears in the THz range . The main features of the gigahertz and terahertz spectra of effective permittivity and electromagnetic interference shielding efficiencies of a MWCNT-based composite observed previously in experiments are systematized and described.

The experimental evidence of the CNT length-dependence of the THz spectra of SWCNT films [3] is also presented and discussed. The experiments have been carried out with films comprising calibrated in length CNTs [4]. We show blue shift of the THz peak in conductivity spectra of SWCNT thin film with decreasing SWCNT length. Thus, experimental results demonstrate the phenomena of localized plasmon resonance in SWCNTs and prove theoretically predicted antenna effect in SWCNTs in terahertz and far-infrared ranges.

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References

1. G.Y. Slepyan , *et al.*, *Phys. Rev. B* **60**, 17136 (1999).
2. G. Ya. Slepyan, *et al.*, *Phys. Rev. B* **81**, 205423 (2010).
3. M. V. Shuba *et al.*, *Phys. Rev. B* **85**, 165435 (2012).
4. M. V. Shuba *et al.*, *Nanotechnology,* **23,** 495714 (2012).

Charge transport in arrays of carbon nanotubes

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Verification of charge transport mechanisms in carbon nanotubes (CNT) arrays is a crucial task for utilizing of their electrical transport properties in devices and sensors. In this report electron transport processes in CNT arrays of different geometry will be discussed. Charge transport mechanisms in single-wall carbon nanotubes and multi-wall carbon nanotubes (MWCNT) arrays were investigated and determined [1]. Terahertz radiation induced hopping conductivity was found in the SWCNT fibers and SWCNT coatings of silica fibers for the first time [2, 3].

Impedance measurements of SWCNT fibers were investigated. It was found that in the low frequency range ($f < 1$ kHz) at low temperatures and at bias voltage $U > 2$ V sign of the imaginary part of impedance was changed from negative to positive, indicating the existence of the crossover from capacitive reactance to inductive one. This crossover was induced by the decrease of height of the energy barriers between nanotubes at the increase of bias voltage. As a result decrease of the impedance of the fibers is accompanied by the rising of the role of kinetic inductance of separate nanotubes [4].

A crossover between metallic ($dR/dT>0$) and non-metallic ($dR/dT<0$) temperature dependence of the resistance as well as low-temperature saturation of resistance in high bias regime was found in CNT based composites [5] and SWCNT films [6, 7].

Quantum corrections to conductivity of SWCNT films were investigated. The magnetoresistance (MR) data demonstrated influence of weak localization (WL) and electron-electron interactions on charge transport properties. The low-field negative MR with positive upturn was observed at low temperatures. At $T > 10$ K only negative MR was observed in the whole range of available magnetic fields. The negative MR can be approximated using 1D WL model. The low temperature positive MR is induced by contribution from electron-electron interactions [7].

References

1. Ksenevich V., Galibert J., Samuilov V. Charge transport in carbon nanotubes films and fibers // In: Carbon Nanotubes, Ed. J. M. Marulanda, p.p. 123-145, INTECH, 2010, ISBN 978-953-307-054-4.
2. V.K.Ksenevich, V.B.Odzaev, D.Seliuta et al. Localization and Non-linear Transport in Single Walled Carbon Nanotubes Fibers // Journal of Applied Physics. 2008. Vol. 104, №8. P.P. 073724(1-7)
3. M.V. Shuba, D. Seliuta, P.P. Kuzhir et al. // Diam. and Rel. Materials. 2012. Vol. 27–28. P. 36–39.
4. Ksenevich V.K., Gorbachuk N.I., Poklonski N.A. et al. Impedance of Single-Wall Carbon Nanotubes Fibers // Fullerenes, Nanotubes, and Carbon Nanostructures. 2012. Vol. 20, № 4. P. 434–438.
5. P. Kuzhir, Ksenevich V.K., A. Paddubskaya et al. // Nanosci. Nanotechn. Lett.. 2011. Vol. 3. P.P. 889.
6. D. Seliuta, L. Subacius, I. Kasalynas, M. Shuba, A. Paddubskaya, V. Ksenevich, P. Kuzhir, S. Maksimenko, and G. Valusis.Electrical conductivity of single-wall carbon nanotube films in strong electric field // J. Appl. Phys. 2013. Vol. 113. P. 183719-1 183719-6.
7. V.K. Ksenevich, M.V. Shuba, and A.G. Paddubskaya. Electrical transport and magnetoresistance in single-wall carbon nanotubes films // Materials Science. 2014. Vol. 20.

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Effects of atomically engineered junction interface on resistive switching performance in Al-WO_x-Al resistive memory

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Resistive Random Access Memory (ReRAM), in which resistance state is switched by the magnitude of external electric field or bias-voltage polarity, is highly expected to be the next generation nonvolatile memory device due to its good non-volatility, simple device structure, and the easy scale-down possibility. Here, we present resistive switching phenomena in Al/WO_x/Al capacitor structures. In order to clarify the effect of the interface formed by the Al electrode and the WO_x film on resistive switching characteristics, we intentionally insert graphene or h-BN single sheet between the Al top electrode and the WO_x film. We clearly demonstrate that the resistive switching characteristics are strongly affected by the nature of the interface. We propose a resistive switching model based on the observed experimental results.

Ion irradiation behavior of nanostructured TiZrAlN-based hard coatings'

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It is known that Al-containing hard coatings based on transition metal nitride (Me–Al–N), in which Al substitutes for Me element in the MeN-based lattice, possess improved tribological and thermal properties. The crystal structure, mechanical and thermal properties of Me–Al–N coatings are strongly determined by the Al content. While keeping cubic lattice, Al content rise leads to improvement of the mechanical properties and to increase in oxidation resistance of the coatings. However, the mechanical characteristics of Me–Al–N coatings become worse when Al content exceeds its maximum solubility in the cubic phase (~ 60 at.%) that is accompanied by a mixed (cubic-NaCl and wurtzite-ZnS) structure formation. We revealed the enhancement of the nanohardness and oxidation resistance of quaternary Ti-Zr-Al-N system when Al concentration increases and coating's structure is characterized as a single-phase c-(Ti,Zr,Al)N solid solution. TiZrAlN thin films (300 nm) with Al content up to 0.36 were deposited using reactive unbalanced magnetron co-sputtering discharges. The influence of Xe ion irradiation (180 keV, 1E15-5E17 cm-2) on structural-phase state of the films was investigated. The increase in Al content resulted in the transformation of structure from single-phase nanocrystalline cubic (c) solid solution ($x<0.12$) to bi-phase nanocomposite ($x=0.14$-0.21) and then to amorphous ($x=0.25$-0.36) one. Nanocrystalline and amorphous ($x=0.36$) structures were stable under irradiation, whereas nanocomposite and amorphous ($x=0.25$) structures transform to nanocrystalline ones. Irradiation of nanocrystalline and nanocomposite films by Xe ions leads to disintegration of c-TiZr(Al)N phase into two coexisting Al-enriched and Al-depleted solid solutions, as a result of radiation-induced separation of the initial metastable solid solution. Xe concentration in the films rises with the increase in the irradiation dose. According to RBS data, the maximum Xe concentration reaches 6.0 at.% in Rp region for the amorphous films ($x=0.25$) at the dose of 5E16 cm-2 while for nanocrystalline films it equals to 4.6 at.%. The increase in resistivity caused by a radiation defects formation and structure modification after ion dose of 5E16 cm-2 is stronger for the nanocrystalline films than for the amorphous film ($x=0.36$). The mechanism of the ion-induced crystallization and segregation in the nanostructural TiZrAlN films is discussed.

Orientation effects in structural and electronic properties of anatase TiO_2 nanowires and nanotubes

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By means of *ab initio* calculations we have revealed the existence of sizable anisotropy in electronic properties of anatase TiO_2 nanowires with respect to orientation: nanowires with <001>, <100> and <110> axes are found to be direct band-gap, indirect band-gap and degenerate semiconductor materials, respectively. The degenerate semiconducting properties of <110>-oriented TiO_2 nanowires are predicted to be an intrinsic feature closely connected with stoichiometry. It is also shown a band-gap variation with nanowire diameter to display rather complex behavior characterized by a competition between quantum confinement and surface states effects that is fully compatible with available contradictory experimental data. Finally, a model to explain the band-gap variation with size in TiO_2 nanowires, nanocrystals and thin films is proposed. In addition, we present results indicating crucial changes in morphology of anatase TiO_2 nanotubes originated from TiO_2 nanowires by making a hole along the wire axis. The critical wall thickness has been found to exist for the nanotubes with <001> and <110> axes: at smaller thickness their shape can be rounded, squeezed, viewed as conglomerates of nanocrystals and even represented as cylindrical and 'single-walled'-like structures formed without rolling up a thin titania layer into a nanotube. In general, band dispersion near the gap region of TiO_2 nanotubes are close to the one of TiO_2 nanowires with the same orientation. We have also revealed that optimization of the unit cell parameter along the wire axis and consideration of quantum confinement and surface states effects are important to provide an interpretation of band-gap variation with respect to wall thickness in TiO_2 nanotubes.

Special Nanoparticles as a Basis to Create Fast-Switching VA LCD's with Wide Viewing Angle

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The problem of improving the response times in LC displays based on nematic liquid crystals is still not resolved. This problem is particularly acute in the VA LCD's with vertical oriented molecules. This is due to the fact that not so many classes of compounds are characterized by a negative dielectric anisotropy. As a result of the optimization of compounds for liquid mixtures with negative dielectric anisotropy the switching times have been reduce down to 7 ms.

Therefore, we have tried to solve this problem by changing the structure of the cell and the conditions of molecular orientation on the substrate surface. For this we decided to use a combination of different ideas and effects. The idea of the vertical orientation of the molecules on anodic porous alumina was taken as a basis [1]. Like other researchers our first results were interesting in terms of improved orientation, but time of reorientation of molecules have been 2-3 times worse [2].

This was expected, since the pores in this case inhibit process of reorientation of the liquid crystal molecules. We hypothesized that this problem can be solved using special type of the diamond nanoparticles with tails. We start to investigate well-known LC materials with such nanoparticles on the substrate with tilted pores. At first we fabricated substrates with ITO and special transparent layers with tilted pores (which can have different diameters and depths). These substrates together with nanoparticles play a role of alignment materials. Because in this case, the nanoparticles are not in the volume of the liquid crystal, they are positioned in the porous and their tails will play a role of alignment materials. Due to a combination of all these materials it is possible to improve the response times of a few times and the viewing angle can reach 180°. Our first results confirmed that this idea can be used for the fabrication of fast-switching VA LCD with wide viewing angle.

References

1. T. Maeda and K.Hiroshima, *Vertically aligned nematic liquid crystal on anodic porous alumina*, Jpn.J.Appl.Phys. {**43**}, L1004 (2004).
2. A. Smirnov, P.Jagiro and V. Lapanik, *Electrochemical fabrication of alignment and multifunction nanostructured layers for LCD's*, Technical Presentation XXIX Eurodisplay 2009, 19 (2009).

Synthesis and characterization of nanoheterostructures based on wide-gap oxides and nanoparticles of chalcogenide semiconductors

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Wide-gap oxide films (ZnO, TiO_2, In_2O_3, SnO_2, etc.) with highly-developed surface sensitized by dye molecules or semiconductor quantum dots are very promising for creation of the third generation of solar cells. In our experiments, the comparative study of nanoheterostructures obtained using *in situ* synthesis of CdS nanoparticles by the successive ionic layer adsorption and reaction technique (SILAR) was done. The films were investigated by SEM, TEM, XRD, BET methods, as well as the UV-Vis and local Raman spectroscopy and complex of photoelectrochemical techniques (photocurrent spectroscopy, voltammetry, etc.). The performed experiments have enabled one to establish and explain both similarities and differences in the properties of the synthesized structures depending on the kind of wide-gap oxide and synthesis method.

Microwave spectroscopy of single-walled carbon nanotube suspension: theory and experiment

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Due to their large conductivity and high aspect ratio, carbon nanotubes can efficiently interact with electromagnetic (EM) radiation in the radiofrequency and microwave ranges. Electromagnetic theory developed for SWCNT suspensions predicts a five-fold gain of the dielectric constant of water at 1 GHz after the addition of a SWCNT solution containing 1 μm long tubes at volume fraction 0.1%, while known experiments demonstrate the gain to be less than 30 %. The discrepancies between theory and measured data can be probably explained by sufficiently strong extent of agglomeration at high nanotubes volume fraction. Systematical research should be done in order to establish the relation between experimentally measured macroscopic parameters of SWCNT-based suspensions and theoretically predicted microscopic EM parameters of individual (isolated) SWCNTs.

The Maxwell-Garnett approach was applied to describe the effective permittivity of SWCNT-based suspensions in the microwave range. It has been shown that the contributions from the metallic and semiconducting SWCNTs to the suspension permittivity can have different absolute values and frequency dependence, and therefore they can be distinguished from each other. We proved experimentally the theoretical outcomes by means of microwave measurements of the permittivity of SWCNT suspensions with two different host liquid media: CHP and 0.1 wt% solution of Triton X-100 in water. The regime of absorption enhancement due to the effect of near field enhancement, predicted for SWCNTs in terahertz [1] and radiofrequency [2] ranges, has been observed in the experiments for both types of suspensions. The theoretical estimations have demonstrated extremely small electromagnetic response of agglomerated SWCNTs as compared with total electromagnetic response from the same quantity of homogeneously dispersed SWCNTs.

References

1. M. V. Shuba, S. A. Maksimenko and G. Ya. Slepyan, *J. Comput. Theor. Nanoscience* **6**(9)**,** 2016-2023 (2009)
2. M.V. Shuba, G. Ya. Slepyan, S. A. Maksimenko, and G. W. Hanson, *J. Appl. Phys.* 108, 114302 (2010).