## Complex Systems Modeling Laboratory

Ihor Lubashevsky
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### Research activity

As previously, in FY2016 the research conduced by the Modeling Complex Systems Laboratory as a whole can be categorized as "Complex System Science," which is a novel interdisciplinary branch of science studying emergent phenomena met in a wide variety of systems different in nature, spanning from traditional objects of the inanimate world and technical systems up to social, economic, and ecological systems, where human or living beings play a crucial role.

**The main research interest of Prof. I. Lubashevsky** concerns the basic principles and mathematical formalism required for describing human behavior, including human memory dynamics, decision-making processes, perception and recognition, prediction, and learning.

In FY2016 the research conducted by Prof. I. Lubashevsky was mainly focused on:

- analysis of the basic properties of human intermittent control over unstable systems based on mathematical modeling and hybrid human-computer experiments;
- mathematical formalism required for modeling human decision-making near the perception threshold that is able to account for the bounded capacity of human cognition;

Among the results obtained in FY2016 the following are worthy of noting.

1. Human behavior in car driving should be categorized as a generalized intermittent control with noise-driven activation. It means that subjects' actions in driving a virtual car can be conceived of as a sequence of alternate fragments of active and passive driver behavior. It is demonstrated that the extended phase space required for modeling human actions in car driving has to comprise four variables: the headway distance, the velocity of car, its acceleration, and the car jerk.

2. An original model for the car-following based on the concept of dynamical trap and the four-dimensional phase space has been developed and demonstrated to be able to reproduce the characteristic features found in the conducted experiments. It should be emphasized that this model does not meet the paradigm of Newtonian mechanics.

3. Within the paradigm of intermittent control human behavior admits the interpretation as a sequence of point-like moments when the operator makes decision on activating or halting the control. These decision-making events may be assumed to be governed by the information about the state of system under control which the operator accumulates continuously. We developed the concept of reinforcement learning with decision inertia which opens a gate to applying the formalism of reinforcement learning to describing human intermittent control. The basic feature of such reinforcement learning is that human behavior in a sequence of selecting available options exhibits quasi-continuous dynamics.

4. The concept of attractor-caused supervenience of the mental upon the physical has been elaborated to demonstrate that the mind and the inanimate world may be independent in their existence within the modern paradigm of their general relationship. The notion of nonlinear relational fields has been proposed to show that meso-level description can possess the very fundamental laws irreducible in any sense to the basic micro-level (if it exists). It is demonstrated that the notion of nonlinear relational fields admits the feasibility of strong emergence and downward causation whose plausible mechanism is a challenging problem for modern science.

5. The concept of emergent mechanism of decision-making near perception threshold as a certain ceteris paribus law has been proposed. This mechanism assumes the universality of human reaction to the uncertainty in evaluating events and is justified using the psychometric function asymptotics found in

our experiments on categorical perception of different shades of gray and the shape recognition.

6. Within the concept of dual-channel multi-component reinforcement learning we have demonstrated that irrational factors, e.g., emotions can be responsible for the chaotic dynamics of the mean characteristics of human choice. It should be emphasized that in the given problem we have met a new class of stochastic processes with chaotic dynamics of the corresponding distribution function.

**The research interests of Prof. I. Khmyrova** in FY2016 was focused on developing analytical and numerical models and simulation strategy for the light extraction through planar semiconductor-air interface of the light-emitting diode (LED). A test simulation of the LED output characteristics was performed and items which need further investigation were determined.

**The research interests of Prof. M. Ryzhii** are in the following areas.

- Theory and computer modeling of graphene based optoelectronic devices.
- Computer modeling of cardiac electrical activity.

## Education activity

In FY2015:

1. Under the supervision of Prof. Lubashevsky two master student and two undergraduate student defended their theses. One of them joined the Modeling Complex Systems Laboratory as a master student.

Member of laboratory taught the following courses:

*Undergraduate courses*:

F3 Discrete Systems;

P4 C++ Programing;

NS7 Introduction to Optoelectronics;

S2 Electric Circuits

O3-015 Computer Simulators and Virtual Experiments on Human Cognition Near Its Threshold

*Graduate courses*:

CSA17 Computer Simulation of Stochastic Processes;

SYA04 Optoelectronics. Computer and Communication Devices;

SYA07 Modeling of Advanced Devices;

SYA06 Advanced Devices for Computer and Communication Systems.

Publications representing the obtained results: [1] (Monograph) I. Lubashevsky, Physics of the Human Mind, Springer, 2017. Comment: This monograph presents a novel point of view on describing human behavior and passed through the review procedure before publication after its revision

[2] (Chapter in Book) I. Lubashevsky, Human Fuzzy Rationality as a Novel Mechanism of Emergent Phenomena, in: Handbook of Applications of Chaos Theory, ed. C.H. Skiadas, C. Skiadas, Chapman and Hall/CRC, 2016, pp. 827-877.

Proceedings (reviewed):

[3] I. Lubashevsky and K. Hijikata, "Statistical Properties of Decision-Making Governed by Reinforcement Learning with Status Quo Bias," In Proceedings of the 48th ISCIE International Symposium on Stochastic Systems Theory and Its Applications, Fukuoka, Nov. 3-4, 2016, p/ 190–196. Abstract: Within the paradigm of human intermittent control over unstable systems human behavior admits the interpretation as a sequence of point-like moments when the operator makes decision on activating or deactivating the control. These decision-making events are assumed to be governed by the information about the state of system under control which the operator accumulates continuously. In the present work we propose the concept of reinforcement learning with decision inertia (the status quo bias) that opens a gate to applying the formalism of reinforcement learning to describing human intermittent control. The basic feature of such reinforcement learning is that human behavior in a sequence of selecting available options exhibits quasi-continuous dynamics. Numerical simulation based on a fairly simple model demonstrates that the proposed formalism does possess the required properties of quasi-continuous behavior.

[4] R. Namae, M. Watanabe, I. Lubashevsky, "Gray Color Multi-Categorical Perception: Asymptotics of Psychometric Function," ibid. p. 76–80 Abstract: The results of conducted experiments on categorical perception with respect to gray color categorization into three classes are reported. Namely, the subjects were

instructed to categorize shades of gray generated in a random sequence into three classes: light-gray, gray, and dark-gray. The collected data are analyzed employing (i) the asymptotics of the constructed psychometric functions and (ii) the mean decision time in categorizing a given gray brightness. The results obtained in the reported experiments and our previous ones are compared and a plausible macro-level mechanism governing gray color categorization is discussed.

[5] A. Zgonnikov and I. Lubashevsky, "Non-equilibrium phase transition in the model of human virtual stick balancing," ibid. p. 20–24: Abstract: Archetypal stick balancing task represents a wide class of unstable processes under human control. The currently dominant theory of human control in stick balancing is based on the concept of discontinuous, or intermittent control. Traditionally, intermittent control models involve threshold-driven control activation, however, recently it has been demonstrated that, in a simple virtual stick balancing task, some basic properties of human control activation mechanisms can only be reflected by more sophisticated, noise-driven models. The aim of the present paper is to demonstrate that the previously introduced double-well model of noise-driven intermittent control activation can reproduce the experimentally observed human behaviour under various conditions. We show that the model successfully reproduces the experimental distributions of actions points (stick angle values triggering activation of human control) obtained in two previously reported experiments. Moreover, we show that a slight change in the model's noise intensity parameter leads to a sudden shift of model distributions, that is, a non-equilibrium phase transition is observed. Our results extend the current understanding of the concept of noise-driven control activation, suggesting that it is applicable in a variety of experimental setups. The two discovered phases of the double-well model correspond to two different modes of control activation in human operators; physiological basis of these modes has to be investigated in future studies.

[6] T. Suzuki, I. Lubashevsky, S. Kanemoto "Cloud Type Interpretation of Statistical Properties of Human Response Delay in Pendulum Balancing", ibid, p. 203–209. Abstract: We present the results of our experiments on studying the probabilistic properties of human response delay in balancing virtual pendulum (stick) with over-damped dynamics. The overdamping eliminates the effects of inertia and, thereby, reduces the dimensionality of the system under control. Two types simulators were employed for studying human response in the stick balancing. One of them hides the stick when it is located in some neighborhood of the upward position, the other just makes the stick unaccessible for subject's control. It enabled us to measure directly the delay time as the time lag between the moment when the pendulum becomes visible or accessible and the moment

when a subject starts to move the mouse. It is demonstrated that the response delay time is characterized by a wide distribution sensitive to the particular details of stick balancing process and its possible correlations in the sequence of actions are ignorable. Besides, in experiments with the second simulator the subject's anticipation is shown to play a significant role in human control. In particular, the formal delay time can take negative values. It poses a question about the applicability of standard formalism of delayed differential equations to describing human intermittent control.

[7] K. Hijikata and I. Lubashevsky, "Reinforcement Learning with Status Quo Bias," in Proceeding of the 8 th International Workshop on Biosignal Interpretation (BSI2016), Osaka, Nov. 1-2, 2016, pp. 201-204. Abstract: Characteristic features of human actions in car driving within the car-following setup are studied using TORCS car-driving simulator. Eight subjects participated in these experiments were instructed to drive a virtual car without overtaking and not losing sight of the lead car in any convenient style. The lead car was driven by computer at a fixed speed. As a main result, we draw a conclusion that human behavior in car driving should be categorized as a generalized intermittent control with noise-driven activation. Besides, we hypothesize that the extended phase space required for modeling human actions in car driving has to comprise four phase variables: the headway distance, the velocity of car, its acceleration, and the car jerk.

[8] I. Lubashevsky and H. Ando, "Intermittent Control Properties of Car Following: Driving Simulator Experiment," ibid, pp. 132-135. Abstract: Characteristic features of human actions in car driving within the car-following setup are studied using TORCS car-driving simulator. Eight subjects participated in these experiments were instructed to drive a virtual car without overtaking and not losing sight of the lead car in any convenient style. The lead car was driven by computer at a fixed speed. As a main result, we draw a conclusion that human behavior in car driving should be categorized as a generalized intermittent control with noise-driven activation. Besides, we hypothesize that the extended phase space required for modeling human actions in car driving has to comprise four phase variables: the headway distance, the velocity of car, its acceleration, and the car jerk.

[9] R. Yamauchi, I. Lubashevsky, H. Ando, "Mesolevel Intermittency of Human Control: Car-Driving Simulator Experiments," ibid, pp. 197-200. Abstract: Based on the open source engine "TORCS" rather simple car-driving simulator was created and used to analyze the basic features of human behavior in car-driving within the car-following setup. Eight subjects with different skill in driving real cars participated in these experiments. They were instructed to drive a virtual car

without overtaking and losing sight of the lead car driven by computer at a fixed speed. In a series of experiments, the lead car speed was set equal to 60, 80, 100, and 120 km/h. In the present work based on the collected data we single out three characteristic styles of car-driving. Namely, we analyze the statistical properties and time patterns of the car pedal position — the pedal position directly reflects subject actions. The discriminated typical styles of driving can be classified as "lsating," "stationary," and the mixture of the previous two. The latter style admits the interpretation as intermittent transitions between the "pulsating" and "stationary"" styles, we call this feature mesolevel intermittency of human control.

[10] T. Suzuki and I. Lubashevksy, "Human Response Delay as a Random Variable: Experiments on Balancing Overdamped Virtual Pendulum," ibid, pp. 193-196. Abstract: We present the results of our experiments on studying the probabilistic properties of human response delay in balancing virtual pendulum with over-damped dynamics. The overdamping eliminates the effects of inertia and, thereby, reduces the dimensionality of the system under control. The created simulator makes the pendulum (stick) invisible when the angle between it and the upward position is less than 5 o . It enables us to measure directly the delay time as the time lag between the moment when the pendulum becomes visible and the moment when a subject starts to move the mouse. It is demonstrated that the response delay time is characterized by a wide distribution sensitive to the particular details of stick balancing process and its possible correlations in the sequence of actions are ignorable. It poses a question about the applicability of standard formalism of delayed differential equations to describing human intermittent control.

## Refereed academic journal

[khmyrova-107-032-01:2016] J. Kholopova E. Polushkin B. Shevchenko Y. Nishidate, I. Khmyrova and S. Shapo-val. Numerical study of light-emitting diode with injected current modulated by designed electrode. *Optical Review*, 23(7):1–8, 2016.

Numerical model and procedure are developed to study the output optical performa nce of light-emitting diode (LED) in which injected current is spatially modulated by mesh-like top metal electrode. The mesh strips have rectangular crossection as in realistic LEDs. The finite element method is applied to obtain three-dimensional distributions of electric potential which are incorporated in the equations for total output power. The numerical procedure is applied to evaluate LED's total output optical power at different geometric parameters of the electrode: the mesh pitch, the width, and the height of the to p mesh-like electrodes. Modeling results demonstrate the effect of mesh pitch variation on the output optical power. In particular, at a certain value of the mesh pitch maximum total output optical power is revealed. The presented approach can be used in optimization of the LEDs with designed metal electrodes.

[khmyrova-107-032-02:2016] A.V. Kovalchuk S. Yu. Shapoval K.V. Maremyanin V.I. Gavrilenko N.A. Maleev V.M. Ustinov V.E. Zemlyakov V.I. Yegorkin V.A. Bespalov V.V. Popov I. Khmyrova. D.M. Yermolayev, E.A. Polushkin. Terahertz response of tightly concatenated two dimensional InGaAs field-effect transistors integrated on a single chip. *International Journal of High Speed Electronics and Systems*, 25(03n04):1640012, 2016.

THz response of AlGaAs/InGaAs/GaAs HEMT structure has been investigated. The structure consists of the serpentine chain of series connected HEMTs. The source of one is the drain for the subsequent transistor. Experiments have been showed THz response peculiarities of such structures and enhanced noise equivalent power.

[khmyrova-107-032-03:2016] A.V. Kovalchuk S. Yu. Shapoval K.V. Maremyanin V.I. Gavrilenko N.A. Maleev V.M. Ustinov V.E. Zemlyakov V.I. Yegorkin V.A. Bespalov V.V. Popov I. Khmyrova. D.M. Yermolayev, E.A. Polushkin. Terahertz response of tightly concatenated two dimensional InGaAs field-effect transistors integrated on a single

chip. *International Journal of High Speed Electronics and Systems*, 25(03n04):1640012, 2016.

THz response of AlGaAs/InGaAs/GaAs HEMT structure has been investigated. The structure consists of the serpentine chain of series connected HEMTs. The source of one is the drain for the subsequent transistor. Experiments have been showed THz response peculiarities of such structures and enhanced noise equivalent power.

[m-ryzhii-107-032-01:2016] V. Ryzhii, M. Ryzhii, M.S. Shur, V. Mitin, A. Satou, and T. Otsuji. Resonant plasmonic terahertz detection in graphene split-gate field-effect transistors with lateral p-n junctions. *Journal of Physics D: Applied Physics*, 49(31,):315103, July 2016.

We evaluate the proposed resonant terahertz (THz) detectors on the basis of field-effect transistors (FETs) with split gates, electrically induced lateral p-n junctions, uniform graphene layer (GL) or perforated (in the p-n junction depletion region) graphene layer (PGL) channel. The perforated depletion region forms an array of the nanoconstions or nanoribbons creating the barriers for the holes and electrons. The operation of the GL-FET- and PGL-FET-detectors is associated with the rectification of the ac current across the lateral p-n junction enhanced by the excitation of bound plasmonic oscillations in the p- and n-sections of the channel. Using the developed device model, we find the GL-FET- and PGL-FET-detector characteristics. These detectors can exhibit very high voltage responsivity at the THz radiation frequencies close to the frequencies of the plasmonic resonances. These frequencies can be effectively voltage tuned. We show that in PL-FET-detectors the dominant mechanism of the current rectification is due to the tunneling nonlinearity, whereas in the PGL-FET-detector the current rectification is primarily associated with the thermionic processes. Due to much lower p-n junction conductance in the PGL-FET-detectors, their resonant response can be substantially more pronounced than in the GL-FET-detectors corresponding to fairly high detector responsivity.

[m-ryzhii-107-032-02:2016] V. Ryzhii, T. Otsuji, M. Ryzhii, V.G. Leiman, G. Fedorov, G.N. Goltzman, I.A. Gayduchenko, N. Titova, D. Coquillat, D. But, W. Knap, V. Mitin, and M.S. Shur. Two-dimensional plasmons in lateral carbon nanotube network structures and their effect on the terahertz radiation detection. *Journal of Applied Physics*, page 044501, 2016.

We consider the carrier transport and plasmonic phenomena in the lateral carbon nanotube (CNT) networks forming the device channel with asymmetric electrodes. One electrode is the Ohmic contact to the CNT network and the other contact is the Schottky contact. These structures can serve as detectors of the terahertz (THz) radiation. We develop the device model for collective response of the lateral CNT networks which comprise a mixture of randomly oriented semiconductor CNTs (s-CNTs) and quasi-metal CNTs (m-CNTs). The proposed model includes the concept of the collective two-dimensional (2D) plasmons in relatively dense networks of randomly oriented CNTs (CNT

[m-ryzhii-107-032-03:2016] V. Mitin, V. Ryzhii, M. Ryzhii, A. Satou, T. Otsuji, and M.S. Shur. Plasmonic enhancement of terahertz devices efficiency. *Int. Journal of High Speed Electronics and Systems*, 25(3-4,):1640019, September 2016.

This paper reviews the plasmonic effects in graphene THz photodetectors (PD) and light emitters (LE). It is demonstrated that the devices based on double graphene-layer (DGL) or multiple graphene-layer structures with the graphene layers separated by thin tunnel barrier layers have advantages over the single graphene-layer (SGL) devices. In DGLs, this advantage is due to the photon-assisted resonant tunneling when the band offset of the graphene layers is aligned to the THz photon energy. The resonant emission or absorption of the THz radiation is enhanced by the cooperative resonant excitation of the graphene plasmons leading to an extremely high gain and/or responsivity in the graphene THz device structures.

[m-ryzhii-107-032-04:2016] M.A. Quiroz-Juareza, R. Vazquez-Medina, E. Ryzhii, M. Ryzhii, and J.L. Aragon. Quasiperiodicity route to chaos in cardiac conduction model. *Communications in Nonlinear Science and Numerical Simulation*, 42(,):370–378, January 2017.

It has been suggested that cardiac arrhythmias are instances of chaos. In particular that the ventricular fibrillation is a form of spatio-temporal chaos that arises from normal rhythm through a quasi-periodicity or Ruelle-Takens-Newhouse route to chaos. In this work, we modify the heterogeneous oscillator model of cardiac conduction system proposed earlier by including an ectopic pacemaker that stimulates the ventricular muscle to model arrhythmias. With this modification, the transition from normal rhythm to ventricular fibrillation is controlled by a single parameter. We show that this transition follows the so-called torus of quasi-periodic route to chaos,

as verified by using numerical tools such as power spectrum and largest Lyapunov exponent.

[m-ryzhii-107-032-05:2016] V. Ryzhii, M. Ryzhii, D. Svintsov, V. Leiman, V. Mitin, M.S. Shur, and T. Otsuji. Nonlinear response of infrared photodetectors based on van der Waals heterostructures with graphene layers. *Optics Express*, 25(5,):5536–5549, March 2017.

We report on the device model for the infrared photodetectors based on the van der Waals (vdW) heterostructures with the radiation absorbing graphene layers (GLs). These devices rely on the electron interband photoexcitation from the valence band of the GLs to the continuum states in the conduction band of the inter-GL barrier layers. We calculate the photocurrent and the GL infrared photodetector (GLIP) responsivity at weak and strong intensities of the incident radiation and conclude that the GLIPs can surpass or compete with the existing infrared and terahertz photodetectors. The obtained results can be useful for the GLIP design and optimization.

## Unrefereed academic journal

[m-ryzhii-107-032-06:2016] M. Ryzhii, A. Satou, and T. Otsuji. Preface (Editorial). *Int. Journal of High Speed Electronics and Systems*, 25(3-4,):1602002, 2016.

This issue contains selected extended papers presented as invited and contributed talks at the RJUSE-TeraTech 2016 symposium. It addresses the variety of topics, in particular, THz detectors based on double heterojunction bipolar transistors (DHBT) and field effect transistors (FET) utilizing resonant plasma effects, quantum cascade (QCL) and HgCdTe quantum-well heterostructures, and graphene-based THz devices.

## Refereed proceedings of an academic conference

[khmyrova-107-032-04:2016] I Khmyrova E. Polushkin V. Zemlyakov B. Shevchenko Yu. Kholopova, Y. Nishidate and S. Shapoval. Light-emitting diodes with designed top metal electrode. In *42nd Int. Conf. on Micro-and Nanoengineering - MNE2016,*, page 62, Vienna, Austria,, Sept. 2016.

In the light-emitting diode(LEDs) with light extraction via top surface the most of light generated beneath top metal electrode is trapped there and cannot be extracted without additional measures. It was reported that mesh-like design of top metal electrode can significantly improve output optical performance of the LED. This paper deals with computer modeling of the effect of mesh-like designed electrode on the LED's output performance.

[khmyrova-107-032-05:2016] A. Kovalchuk E. Polushkin B. Shevchenko I. Khmyrova, Yu. Kholopova and S. Shapoval. Effect of nonunform current injection on electroluminescence spectra of InGaN/GaN blue- green light-emitting diode. In *Abstracts of 43rd Int. Symp. on Compound Semiconductors - ISCS2016*, page 58, Toyama, Japan, June 2016.

Blue-green InGaN/GaN light-emitting diodes (LEDs) with spatially nonuniform current injection were fabricated and tested. Broad electroluminescence (EL) spectra with equal peak intensities of blue and green emission lines and shallow trough between them were observed at elevated injected current. These features of EL- spectrum are believed to be caused by the mesh-like patterning of the electrode as it creates spatially nonunform electric potential which provides spatial modulation of the injected current along the QW-planes. The latter results not only in spatial nonuniformity of intensity of generated light along the QW-planes but due to screening of polarization field in the QWs causes also position-dependent blue shift of EL. The observed phenomenon can be used to control the EL spectra of dual-wavelength LEDs by the patterned electrodes.

[khmyrova-107-032-06:2016] K. V. Maremyanin V. I. Gavrilenko N. A. Maleev V. M. Ustinov V. A. Bespalov V. E. Zemlyakov V. I. Egorkin B. Shevchenko I. Khmy-rova D. M. Yermolaev, V. V. Popov and S. Yu. Shapoval. Detection of terahertz radiation by array of integrated field- effect transistors with floating electrodes. In *9th Global Symposium on Millimeter-Waves (GSMM 2016) and The 7th ESA Workshop on Millimetre-Wave Technology and Applica- tions*, Espoo, Finland., June 2016.

Array of field-effect transistors ˜(FET) with asymmetric T-gates and floating electrodes fabricated on a single chip was used as terahertz (THz) detector. Nonresonant detection with strong photovoltaic response was realized due to excitation of electron plasma oscillations in the common channel of the FETs array. Voltage responsivities obtained by the array of FETs with

floating electrodes surpass the photoresponse reported for the array of FETs connected in series by external wiring.

[khmyrova-107-032-07:2016] K. V. Maremyanin V. I. Gavrilenko N. A. Maleev V. M. Ustinov V. A. Bespalov V. E. Zemlyakov V. I. Egorkin B. Shevchenko I. Khmy-rova D. M. Yermolaev, V. V. Popov and S. Yu. Shapoval. Detection of terahertz radiation by array of integrated field- effect transistors with floating electrodes. In *9th Global Symposium on Millimeter-Waves (GSMM 2016) and The 7th ESA Workshop on Millimetre-Wave Technology and Applica- tions*, Espoo, Finland., June 2016.

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[khmyrova-107-032-08:2016] A. Kovalchuk B. Shevchenko I. Khmyrova Y. Nishidate, J. Kholopova and S. Shapoval. Modeling of light-emitting diode with nonuniform current injection. In *Numerical Simulation of Optoelectronic Devices- NUSOD 2016*, pages 171–172, Sidnei, Australia, July 2016.

Light-emitting diode (LED) with nonuniform current injection caused by the mesh-like design of top metal electrode is studied numerically. Three-dimensional Laplace equation for electric potential is solved by finite element method. The numerical model incorporates mapped infinite element to account for potential decay far away from the LED structure and finite element model developed for boundary condition at semiconductor-air interface in the mesh opening. Simulation results demonstrate the effect of the mesh geometrical parameters on the total output power

[khmyrova-107-032-09:2016] A. Kovalchuk E. Polushkin B. Shevchenko I. Khmyrova Y. Nishidate, J. Kholopova and S. Shapoval. Effect of designed top p-electrode on output performance of LED by numerical modeling. In *2016 IEEE Photonics Conf. and 29th Annual Conf. of the IEEE Photonics Society*, pages WP–17, Hawaii,USA, Oct/ 2016.

Impact of mesh-like top metal electrode on output performance of light-emitting diode (LED) is studied using developed numerical model. Three-dimensional Laplace equation is solved by FEM method. Modeling results demonstrate that effect of mesh pitch variation dominates over strip height variation.

[m-ryzhii-107-032-07:2016] T. Otsuji, A. Dubinov, V.Y. Aleshkin, D. Svintsov, M. Ryzhii, S. Boubanga Tombet, D. Yadav, A. Satou, V. Mitin, M.S. Shur, and V. Ryzhii. Graphene-based van der Waals heterostructures for emission and detection of terahertz radiation. In M.F. Anwar, T.W. Crowe, and Editors T. Manzur, editors, *Proceedings of SPIE - The Int. Society for Optical Engineering: Terahertz Physics, Devices, and Systems X: Advanced Applications in Industry and Defense*, volume 9856, page 985603, Baltimore, United States, April 2016. SPIE, SPIE.

This paper reviews recent advances in the research of graphene-based van der Waals heterostructures for emission and detection of terahertz radiation. A gated double-graphene-layer (DGL) nanocapacitor is the core shell under consideration, in which a thin tunnel barrier layer is sandwiched by outer graphene layers at both sides. The DGL can support symmetric optical and anti-symmetric acoustic coupled plasmon modes in the GLs. The latter mode can modulate the band-offset between the GL, giving rise to modulation of the inter-GL-layer resonant tunneling. This can dramatically enhance the THz gain or responsivity via plasmon-assisted inter-GL resonant tunneling.

[m-ryzhii-107-032-08:2016] I. Semenikhin, V. Vyurkov, A. Bugaev, R. Khabibullin, D. Ponomarev, A. Yachmenev, P. Maltsev, M. Ryzhii, T. Otsuji, and V. Ryzhii. Sn nanothreads in GaAs: Experiment and simulation. In V.F. Lukichev and Editors K.V. Rudenko, editors, *Proceedings of SPIE - The Int. Society for Optical Engineering: Int. Conference on Micro- and Nanoelectronics - 2016 (ICMNE 2016)*, volume 10224, page 102240R, Zvenigorod, Russian Federation, October 2016. SPIE, SPIE.

The gated GaAs structures like the field-effect transistor with the array of the Sn nanothreads was fabricated via delta-doping of vicinal GaAs surface by Sn atoms with a subsequent regrowth. That results in the formation of the chains of Sn atoms at the terrace edges. Two device models were developed. The quantum model accounts for the quantization of the electron energy spectrum in the self-consistent two-dimensional electric potential, herewith

the electron density distribution in nanothread arrays for different gate voltages is calculated. The classical model ignores the quantization and electrons are distributed in space according to 3D density of states and Fermi-Dirac statistics. It turned out that qualitatively both models demonstrate similar behavior, nevertheless, the classical one is in better quantitative agreement with experimental data. Plausibly, the quantization could be ignored because Sn atoms are randomly placed along the thread axis. The terahertz hot-electron bolometers (HEBs) could be based on the structure under consideration.

[m-ryzhii-107-032-09:2016] G. Tamamushi, T. Watanabe, A.A. Dubinov, J. Mitsushio, H. Wako, A. Satou, T. Suemitsu, H. Fukidome, M. Suemitsu, M. Ryzhii, V. Ryzhii, and T. Otsuji. Single-mode terahertz emission from current-injection graphene-channel transistor under population inversion. In *72th Annual Device Research Conference (DRC)*, page 7548491, University of Delaware, Newark United States, August 2016. DRC, IEEE.

Optical and/or injection pumping of graphene can enable negative-dynamic conductivity in the terahertz (THz) spectral range, which may lead to new types of THz lasers. In the graphene structures with p-i-n junctions, the injected electrons and holes have relatively low energies compared with those in optical pumping, so that the effect of carrier cooling can be rather pronounced, providing a significant advantage of the injection pumping in realization of graphene THz lasers. We implement a forward-biased graphene structure with a lateral p-i-n junction in a distributed-feedback dual-gate graphene-channel field-effect transistor (DFB-DG-GFET) and experimentally observe a single mode emission at 5.2 THz at 100K. The device exhibits a nonlinear threshold-like behavior.

[m-ryzhii-107-032-10:2016] M. Ryzhii, V. Ryzhii, A. Satou, T. Otsuji, V. Mitin, and M.S. Shur. Models for plasmonic THz detectors based on graphene split-gate FETs with lateral p-n junctions. In P. Pichler, E. Bar, and Editors J. Lorenz, editors, *Int. Conference on Simulation of Semiconductor Processes and Devices (SISPAD)*, pages 361–364, Nuremberg, Germany, September 2016. German Research Foundation (DFG), IEEE.

We propose and analyze the resonant plasmonic terahertz detectors based on the split-gate field-effect transistors with electrically induced p-n junctions and graphene and perforated graphene channels. The perforation of

the p-n junction depletion region leads to the tunneling suppression and the substantial reinforcement of the detector resonant response.

[m-ryzhii-107-032-11:2016] G. Tamamushi, T. Watanabe, A.A. Dubinov, H. Wako, A. Satou, T.-S. Suemitsu, M. Ryzhii, V. Ryzhii, and T. Otsuji. 5.2-THz single-mode lasing in current-injection distributed-feedback dual-gate graphene-channel field-effect transistor. In *41st Int. Conference on Infrared, Millimeter and Terahertz Waves (IRMMW-THz)*, page 7758354, Copenhagen, Denmark, November 2016. IEEE Computer Society.

A distributed-feedback (DFB) dual-gate graphene-channel field-effect transistor was fabricated as a current-injection terahertz laser. A single mode emission at 5.2 THz was observed at 100K beyond the threshold carrier injection level. Spectral narrowing with increasing the carrier injection around the threshold was also observed. The result is still preliminary level but the linewidth fairly agrees with numerical simulation based on DFB-Fabry-Perrot hybrid-mode modeling.

[m-ryzhii-107-032-12:2016] M. Ryzhii and E. Ryzhii. Simulink heart model for simulation of the effect of external signals. In *13th IEEE Int. Conference on Computational Intelligence in Bioinformatics and Computational Biology (CIBCB)*, page 7758102, Chiang Mai, Thailand, October 2016. IEEE, IEEE.

In this work, we propose an extended MATLAB/Simulink version of heterogeneous oscillator heart model for simulation of the effect of applied external highf-requency stimulation on the cardiac conduction system and demonstrate some simulation results applying signals with different amplitude, frequency and duration. Using the model we observe reversible and irreversible conduction blocks as well as initiation and termination of atrial and ventricular fibrillations. The proposed model can be used for research, educational and testing purposes.

[m-ryzhii-107-032-13:2016] G. Tamamushi, T. Watanabe, A.A. Dubinov, H. Wako, A. Satou, T. Suemitsu, M. Ryzhii, V. Ryzhii, and T. Otsuji. Current-injection terahertz lasing in distributed-feedback dual-gate graphene-channel field-effect transistor. In *2016 Conference on Lasers and Electro-Optics (CLEO)*, page 7788714, San Jose, United States, December 2016. OSA, IEEE.

In this communication, we implemented a forward-biased graphene structure with lateral p-i-n junctions in a distributed-feedback dual-gate graphene-channel field effect transistor (DFB-DG-GFET) and experimentally observed a single mode emission at 5.2 THz at 100K. The device exhibits a nonlinear threshold-like behavior with respect to the current-injection level. The observed spectral line width agrees well with the modal gain analysis based on DFB-Fabry-Perrot hybrid-mode modeling. Although the results obtained are still preliminary level, the observed emission is interpreted as THz lasing in population-inverted graphene by carrier-injection.

[m-ryzhii-107-032-14:2016] G. Tamamushi, T. Watanabe, J. Mitsushio, A.A. Dubinov, A. Satou, T. Suemitsu, M. Ryzhii, V. Ryzhii, and T. Otsuji. Current-injection terahertz lasing in a distributed-feedback dual-gate graphene-channel transistor. In Editor M. Razeghi, editor, *Proceedings of SPIE: Quantum Sensing and Nano Electronics and Photonics XIV 2017*, page 1011126, San Francisco, United States, January 2017. SPIE, SPIE.

This paper reviews recent advancement on the research toward graphene-based terahertz (THz) lasers. Optical and/ or injection pumping of graphene can enable negative-dynamic conductivity in the THz spectral range, which may lead to new types of THz lasers. A forward-biased graphene structure with a lateral p-i-n junction was implemented in a distributed-feedback (DFB) dual-gate graphene-channel FET and observed a single mode emission at 5.2 THz at 100K. The observed spectral linewidth fairly agrees with the modal gain analysis based on DFB-Fabry-Perrot hybrid-cavity-mode modeling. Although the results obtained are still preliminary level, the observed emission could be interpreted as THz lasing in population-inverted graphene by carrier-injection.

## Research grants from scientific research funds and public organizations

[m-ryzhii-107-032-15:2016] M. Ryzhii (collaborator). "Development and application of the new principle terahertz optoelectronic devices based on two-dimensional atom thin film heterojunction", 2016-2020.

## Academic society activities

[m-ryzhii-107-032-16:2016] M. Ryzhii, Dec. 1996-present.

Senior Member

[m-ryzhii-107-032-17:2016] M. Ryzhii, July 1995.

Member (lifelong)

[m-ryzhii-107-032-18:2016] M. Ryzhii, 2016.

Reviewer for Physica B journal

[m-ryzhii-107-032-19:2016] M. Ryzhii, 2016.

Reviewer for Computer Methods and Programs in Biomedicine journal

[m-ryzhii-107-032-20:2016] M. Ryzhii, August 2016.

Reviewer for Joint Int. Conference of Big Data Analytics in Health Informatics 2016 (BDAHI 2016) and the 13th Int. Conference on Ubiquitous Healthcare (u-Healthcare 2016)

[m-ryzhii-107-032-21:2016] M. Ryzhii, 2016.

Reviewer for European Physical Letters journal

## Contribution related to student management(for example, solution of a student-related problem)

[m-ryzhii-107-032-22:2016] Student Class Mentor (C1-A) 04.2015-03.2017

## Contribution related to planning administration for research, research conferences, or international research

[m-ryzhii-107-032-23:2016] Member of the Organizing Committee and Program Committee Member of RIEC Int. Symposium "5th Russia-Japan-USA-Europe Symposium on Fundamental and Applied Problems of Terahertz Devices and Technologies" (RJUSE TeraTech-2016), Tohoku University, Sendai

[m-ryzhii-107-032-24:2016] Program Committee Member of "Applied Nanotechnology and Nanoscience" Int. Conference (ANNIC 2016), Barcelona, Spain

[m-ryzhii-107-032-25:2016] Reviewer for the European Research Council - Consolidator Grant on Graphene Laser Research (EUR 2 Million)

Summary of Achievement

## Other significant contribution toward university planning, management, or administration

[m-ryzhii-107-032-26:2016] UoA Library Committee member, 2016