INTERNATIONAL SEMINAR ON ELECTRON DEVICES DESIGN AND PRODUCTION

PROCEEDINGS

APRIL 23-24, 2019
PRAGUE, CZECH REPUBLIC

International Seminar on Electron Devices Design and Production (SED-2019)

April 23–24, 2019
Prague, Czech Republic
sed.diag.ru

Seminar schedule

April 23, Tuesday		
9:00 – 10:00	Registration of participants	
10:00 – 13:00	PLENARY OPEN SESSION	
13:00 – 14:00	Coffee Break (Lunch)	
14:00 – 17:30	**Computer-Aided Design and Production of Electron Devices**	**Ensuring the Quality and Reliability of Electronics Devices**
17:30 – 19:30	Get Together Party	
April 24, Wednesday		
10:00 – 13:00	**Electronics Manufacturing Services**	
13:00 – 14:00	Coffee Break (Lunch)	
14:00 – 17:30	**Electronics Manufacturing Services**	
April 25, Thursday		
Social Program		

Organized by
- MIREA - Russian Technological University (RTU MIREA)
- Russian Centre of Science and Culture in Prague
- Russian Section of the Institute of Electrical and Electronics Engineers (IEEE);
- The IEEE Tomsk Chapter & Student Branch.

Sponsors
- Experimental laboratory NaukaSoft

Location:

Seminar will be carried out at the Russian Science and Culture Centre (RSCC) in Prague (Praha 6, ul. NaZátorce 16)

Russian science and culture centre (created in 1971) is one of the Rossotrudnichestvo foreign representations (Federal Agency for the Commonwealth of Independent States, Compatriots Living Abroad and International Humanitarian Cooperation).

The preparation and realization programs of the sphere of science, culture and education, Russian language advancement, outreach of Russian achievements in these spheres are the major RSCC activities.

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Key objectives of the seminar:

1. Computer-Aided Design and Production of Electronic Devices
2. Electronics Manufacturing Services
3. Ensuring the Quality and Reliability of Electronic Devices

Guidelines for Oral Presentations

Please note that the overall time available for your presentation is limited to 10 minutes allowed for the actual presentation and 5 minutes for discussion. You should plan your presentation carefully. You should select your vocabulary to address as wide an audience as possible and avoid unfamiliar abbreviations or expressions. Your oral presentation should be performed in the way of answers the following questions:

Why was the project undertaken?
What was done?
What was learned?
What does it mean?

Remember, the three rules for an effective presentation are:

- Tell them what you are going to say (spend a few moments introducing your topic and what you intend to speak about).
- Tell them (deliver your talk, including the methods, results and conclusions)
- Tell them what you said (summarize the most important points of your lecture).

Please remember that the responsibility of having your paper ready for Presentation at the scheduled time is primarily in your hands as the presenter. Check the readability, completeness and order of your slides before your presentation. Arrive well in advance of the session, and acquaint yourself with the operation of the podium and location of the equipment. Seminar staff will be present to assist you. There are no scheduled breaks in the agenda so it is mandatory that the presentations be loaded before the beginning of each session.

Be careful to speak in accordance with the sequence of your slides. Avoid making major modifications to your transparencies during your presentation. Do not use more than 1 slide per minute. Please stay within the time limit allocated for your presentation.

Technical equipment provided in the Conference room are:

- Multimedia video projector;
- Projection screen;
- Standard multimedia PC with CD-ROM drive.

The operating system for session computers is Microsoft Windows XP. The available software is Microsoft Office 7 (or newer) that includes Word, Excel, PowerPoint, Adobe Acrobat Reader, and Windows Media Player. Therefore, all presentations must be compatible with these packages. Slide and overhead projectors will not be available!

Plenary session (I^{2}T and SED)

1. Atanas Kostadinov
   Technical University - Sofia, Bulgaria
   About Marie Curie Alumni Association

2. Yasuto Hijikata
   Saitama University, Japan
   Room temperature electronic-driven quantum devices using single defects in silicon carbide semiconductors

3. Zhuravlev V.Ph. Perelyaev S.E.
   Ishlinsky Institute for Problems in Mechanics of the Russian Academy of Sciences
   3-D MICROMACHINED SPHERICAL SHELL RESONATORS: IMPLEMENTATION VISION

4. Perelyaev S.E., Zhuravlev V. Ph.
   Ishlinsky Institute for Problems in Mechanics of the Russian Academy of Sciences
   MEMS Integrating gyroscope and angular velocity sensor (AVS) based on 2D micro-wineglasses and 3D micro-spheres

5. Alla G. Kravets, Natalia A. Salnikova, Ilya P. Mikhnev, Nazim Y. Orudjev, Olga V. Poplavskaya
   Volgograd State Technical University
   Web Portal for Project Management in Electronics Design Software Development

Section meeting

	Computer-Aided Design and Production of Electronic Devices April 23, Tuesday, 14:00 – 17:30	
c101	Pavel N. Anisimov, Denis A. Kuzin	Application of Experiment Planning Methods for Building a Network of Digital Television Broadcasting of DVB-T2 Standard
c102	Vadim A. Zhmud, Lyubomir V. Dimitrov, Oleg V. Stukach	Investigation of the Numerical Optimization Toolkit for Control of the Oscillatory Unstable Object
c103	Yury Shornikov, Evgeny Popov	Modeling and Simulation of Electronic Devices in the ISMA Environment
c104	Elena P. Dogadina, Yuriy A. Kropotov, Aleksander Y. Proskuryakov	A model of simultaneous optimization of production planning
c105	Viktor M. Kureychik, Irina B. Safronenkova	Ontology-based approach to design problem formalization
c106	N.V. Butyrlagin, N.V. Chernov, N.V. Prokopenko, A.V. Bugakova	Current Digital Logical Elements' Synthesis and Circuitry: Linear Threshold Approach

c107	Yury N. Kofanov, Svetlana Y. Sotnikova	The Foresight Modeling in Ensuring High Quality of Space Electronic Equipment
c108	Irina Safonova, Elizaveta Dmitrieva, Boris Zhelenkov, Yakov Goldovsky	Taking Project Decisions in Computer Aided Design of Electronic Computing Equipment Modules
c109	Elmar Kuliev, Vladimir Kureichik, Vladimir Kureichik Jr.	Mechanisms of swarm intelligence and evolutionary adaptation for solving PCB design tasks
c110	A.G. Kravets, N. A. Salnikova, I.P. Mikhnev, N.Y. Orudjev, O.V. Poplavskaya	Web Portal for Project Management in Electronics Design Software Development
c111	Dmitry Bulakh, Sergey Zhestkov	Logic gates placement algorithm for visualization of integrated circuits netlists
c112	Kiya Bushmeleva, Svetlana Uvaysova, Aida Uvaysova, Oksana Avdeuk	The System of Automated Circuit Simulation of Electronic Devices
c113	Fedor Polishchuk	Development and research methods of calculation induced interference in the onboard network of spacecraft
c114	Daria Zaruba, Dmitriy Zaporozhets, Nina Kulieva	Glowworm Swarm Optimization Algorithm for Computer Equipment Partitioning
c115	Vladimir Kureichik Jr., Victoria Bova, Vladimir Kureichik	Hybryd Approach for Computer-Aided Design Problems
c116	Alina Kulgina, Darya Sharova, Aleksandr Vostrikov, Ekaterina Prokofeva	Development of software module for the analysis of electrical circuits
c117	Y.N. Kofanov, Y.A. Vinokurov, S.Y. Sotnikova	Optoelectronic Devices' Thermal Working Modes Providing Method
c118	V.V. Martynov, E.S. Zakieva, A.A.Petunin	Modeling the Initial Shape in the Tasks of Automating the Design of Electronic Means Placement on a Flat Material
f250	Daniil E. Shumakher, Galina V. Nikonova, Liia V. Shchapova	Radiosignal Identification System For The Software-Defined Radio

	Ensuring the Quality and Reliability of Electronic Devices **April 23, Tuesday, 14:00 – 17:30**	
q301	Dmitry Lovtsov, Dmitry Gavrilov	Automated special purpose optical electronic system's functional diagnosis, quality and informational performance index estimation
q302	Oleg V. Stukach, Raushan Zh.	Model of the Yield Loss Factors Based on Survey Analysis for the Integrated Circuits Manufacturing

	Aimagambetova	
q303	Farkhad A. Abdullin, Valeriy E. Pautkin, Ekaterina A. Pecherskaya, Anatoliy V. Pecherskiy, Dmitriy V.Artamonov, Kirill O. Nikolaev	Application of the Selective Silicon Etching Methods for Estimation of the Wafers Quality in the Micromechanical Sensors
q304	Alexey A. Shamin, Ekaterina A. Pecherskaya, Kirill O. Nikolaev, Timur O. Zinchenko, Yuliya V. Shepeleva, Aleksei A. Golovyashkin	Quality Control of Technological Processes of Manufacturing Functional Solar Cells Layers Based on Hybrid Organic-Inorganic Perovskites
q305	Yulia Logunova, Viktor Kureichik	Algorithm of Graph Planarity Defenition for Improving the Quality of the Very Large Scale Integrations Circuits Tracking.
q306	I.Makarova, E.Mukhametdinov, L. Gabsalikhova, R.Garipov, A.Pashkevich, K.Shubenkova	Justification of the Possibility to Use Vibration Measuring Sensors in Onboard Diagnostic Devices
q307	K. Palaguta, V. Bebenin, A. Kuznecov	Testing of the device of the help to visually impaired people for positioning in space
q308	Lysenko A.V., Trusov V.A., Tankov G.V., Kochegarov I.I., Danilova E.A.	An Algorithm for the Implementation of an Adaptive Vibration Testing System of Onboard Radio-Electronic Equipment
q309	Lysenko A.V., Yurkov N.K., Goryachev N.V., Danilova E.A., Lapshin E.V.	An Adaptive Vibration Testing System of Structural Elements of Radio-Electronic Equipment
q310	Igor Lushpa, Konstantin Novikov, Sergey Polesskiy	The Reliability Characteristics of the Data Processing Centers Cooling Systems
q311	Ishkov Anton, Solodimova Galina	Measuring complex for testing pulsed thermoelectronic training of electronic components
q312	Chesalin A.N., Grodzenskiy S.Ya.	The Algorithm Of Calculating The Refined Boundaries Of Sequential Criteria Based On The Likelyhood Ratio
q313	S.Polesskiy, P.Korolev, K.Sedov, I.Ivanov	Development of methods for identifying factors affecting the electronic tools reliability in the design
q314	B.Kenzhaliyev, K.Ozhikenov, A.Ozhikenova, O.Bodin, L.Krivonogov, D.Papshev	Improving the Interference Tolerant Noise Immunity of Ambulatory Telemetry ECG Diagnostics Systems

	Electronics Manufacturing Services **April 24, Tuesday, 10:00 – 17:30**	
m201	U.A. Konstantinov, E.D. Pozhidaev, S.R. Tumkovskiy	Investigation of Electrostatic Discharge Effect on High-power Mosfet-Transistors Considering the Influence of PCB
m202	Atanas Kostadinov, Vitali Guitberg, Morten Olavsbraten, Guennadi Kouzaev	Multi-Logics Gates
m203	Abaturov Vladimir Vladimirovich, Savelyev Igor Ivanovich, Skopin Constantin Alexandrovich	Thermal model of Zeeman ring laser
m204	A.R. Bestugin, O.M. Filonov, I.A. Kirshina, N.A. Ovchinnikova	Design of micro – and nanoelectromechanical resonators taking into account internal temperature fields
m205	Aleksandr F. Kryachko, Yuliana A. Novikova, Maksim B. Ryzhikov, Elizaveta V. Kucherova	Research of perspective materials for thin optical films for the mid-IR
m206	Yelizarov A.A., Nazarov I.V., Skuridin A.A.	Application of a Cylindrical Resonator for Measuring the Parameters of Dielectric Materials
m207	Alexandra V. Salnikova, Vladimir P. Litvinenko, Boris V. Matveev, Alexey N. Glushkov, Yuliya V. Litvinenko, Alexander A. Makarov	The Fast Digital Algorithm for Measuring the Parameters of the Random Processes
m208	Maxim Yu. Shtern, Maxim S. Rogachev, Yury I. Shtern, Alexey A. Sherchenkov, Alexander O. Kozlov	Creation of multisectional thermoelements for increasing of the efficiency of thermoelectric devices
m209	S.E. Perelyaev, V. Ph. Zhuravlev	MEMS Integrating gyroscope and angular velocity sensor (AVS) based on 2D micro-wineglasses and 3D micro-spheres
m210	Ibrahim Ibrahim Nizar	Investigation of Inverse kinematics Solution for a Human-like Aerial Manipulator Based on The Metaheuristic Algorithms
m211	Chernyshov N.N., Belousov A.V., Grebenik A.G.	Spin-Dependent Tunneling in Semiconductor Structures Without an Inversion Center
m212	N.N. Chernyshov, A.V. Belousov, I.N.	Spin Resonance in a Semiconductor Structure in Quantizing Magnetic Field

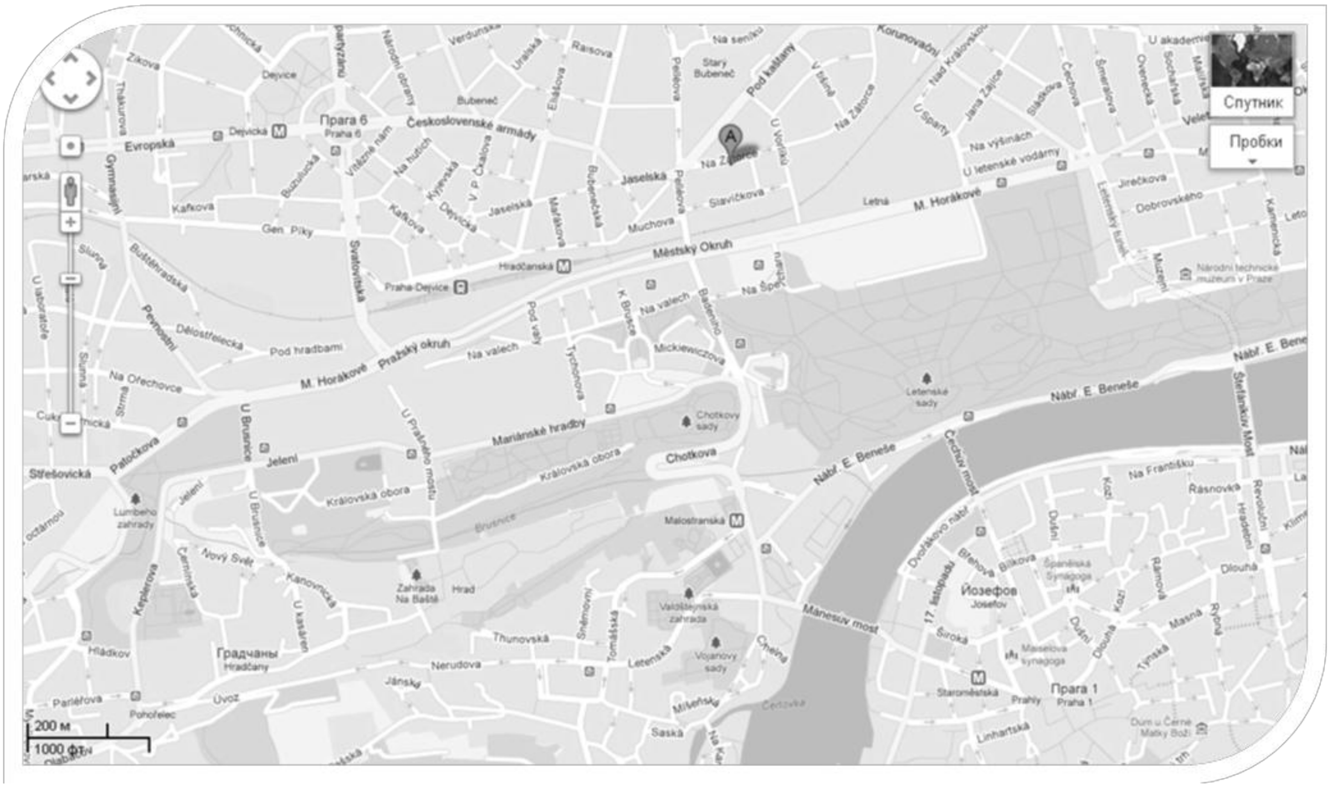
	Gvozdevskiy, N.I. Slipchenko, M.A.F. Alkhawaldeh	
m213	Valentin Ashmarin, Yevgeniya Tyryshkina	Conductivity of Fiberglass after Long-Term Exposure to Vacuum
m214	Ilya Agapov, Margarita Afanasyeva	Experimental Determination of the Electric Field Gain Coefficient on the Top of the Spherical Electrode on Air
m215	Vladimir Petrosyan, Alexander Belousov, Artem Grebenik	Solution of the Stefan problem during radiation-conductive heat transfer in the process of growing sapphire single crystals by a modified Kyropoulos method
m216	Riabyshenkov Andrei, Karakeyan Valery, Zaharov Artem, Larionnov Nikolay	Exergy analysis of the recirculation scheme for air preparation of clean rooms based on a system approach
m217	Bagdaulet K. Kenzhaliyev , Kassymbek A. Ozhikenov, Aiman K. Ozhikenova, Oleg N. Bodin, Mikhail N. Kramm, Fahim K. Rahmatullov	Reconstruction of Equivalent Electric Heart Generator
m218	Boloznev V.V., Zastela M.Yu., Chabdarov Sh.M., Yurkov N.K., Bannv V.Y.	To the Problem of Vibration Resistance Ensuring of Microwave Radio Receivers
m219	F.R. Ismagilov, V.E. Vavilov, I.F. Sayakhov	The electromagnetic and thermal analysis of electrical machines from composite materials
m220	Tychkov Alexander, Kochegarov Igor, Goryachev Nickolay	Design Of An Instrumentation Amplifier For A Mobile Electrocardiogram Recorder With Autonomous Power Supply
m221	Vasiliy Berdnikov, Valeriy Lokhin, Saygid Uvaysov	Determination of Guaranteed Stability Regions of Systems with a PID Controller and a Parametrically Perturbed Control Object
m222	Victor E. Voitovich, Alexander I. Gordeev, Nikolay N. Prokopenko, Anna V. Bugakova	Prospects for Development of Fast Recovery Power GaAs SBD on the basis of LPE-Technology
m223	Victor E. Voitovich, Alexander I. Gordeev, Ahmet B. Saytiev, Igor A. Sysoev	Extreme, based on new physical principles, high-bandwidth, high-efficiency photovoltaics and hyper-speed power electronics on LPE GaAs single crystals
m224	Trofimov A. A., Bezborodova O. E., Gromkov N. V., Polosin V. G., Spirkin	Magnetodiode-Based Speed-of-Rotation Transducers

	A. N.	
s230	Tatyana Murashkina, Tatyana Istomina, Anna Shcherbakova, Pavel Tsarev	The Energetic Estimate of Optical Fiber Measuring System for Determination of the Fluid Composition
s231	Ekaterina A. Polyakova, Tatiana I. Murashkina, Elena A. Badeeva, Sergey I. Torgashin, Natalya N. Yankina	Principles of Reliability Improvement of Fiber-Optic Sensors for Rocket and Space Equipment and Aeronautical Engineering
s232	Alexander Chernodarov, Olga Khalyutina, Andrew Patrikeev	Monitoring and Optimization of the Structure of a Navigation System on a Set of MEMS Sensors
s233	E.A. Badeeva, T.I. Murashkina, D.I. Serebryakov, T.Yu. Brostilova, I.E. Slavkin	Fiber-optic pressure sensors with an open optical channel for rocket-space and aviation engineering
s234	Maxim Yu. Shtern, Ivan S. Karavaev, Yury I. Shtern, Sergey. P. Timoshenkov, Artem V. Makshakov	The structurally-technological principles of creation for smart sensors of thermodynamic parameters
s235	A.Sh. Rakhmatulin, V.D. Popov	Integral microaccelerometer based on GaAs / InAs
s236	Alina M. Esimkhanova, Galina V. Nikonova, Olga A. Nikonova	Fiber And Optical Sensors Of Information And Measuring Systems
i240	Nikita Chuvaldin, Bogdan Belogurov, Alexey Rolich, Ilya Motajlenko	Study of energy harvesting using high-frequency emitting for IoT
i241	Tatyana Istomina, Anatoly Nikolsky, Elena Petrunina, Anatoly Svetlov, Elmin Bayramov, Boris Chuvykin	Car Internet cyberbiological system for persons with disabilities
i242	Igor Lvovich, Yuriy Preobrazhenskiy, Yakov Lvovich, Oleg Choporov, Andrey Preobrazhenskiy	Managing developing Internet of things systems based on models and algorithms of multi-alternative aggregation
i243	Grishko A.K., Buts V.P., Rybakov I.M., Dolotin A.I., Brostilov S.A.	Principles of Mathematical Logic for Multi-Agent Control of Intellectual Mobile Objects and Systems In the Dynamic Environment
i244	Valery A. Kokovin,	Intelligent Power Electronic Converter For Wired and

	Vladimir I. Diagilev, Jaroslav Halík, Svetlana S. Uvaysova	Wireless Distributed Applications
f250	Daniil E. Shumakher, Galina V. Nikonova, Liia V. Shchapova	Radiosignal Identification System For The Software-Defined Radio
f251	Konstatntin S. Kalashnikov, Yury N. Bugaev, Vladimir A. Ivanov, Alexandra V. Salnikova, Oleg V. Chernoyarov,	The Phase Measurements Disambiguation by Means of the Two Paths Similarity Method
f252	Artyushenko Vladimir Mikhaylovich, Volovach Vladimir Ivanovich	Permissible interference power from earth station equipment within 3400-4200 MHz band
f253	Artyushenko Vladimir Mikhaylovich, Volovach Vladimir Ivanovich	Evaluation of electromagnetic compatibility between earth stations and network of wireless access in the band 3400-4200 MHz
f254	Il'ya Boykov, Pavel Aikashev	To the numerical method for synthesis of fractal antennas
f255	Egor Gurov , Aida Uvaysova, Saygid Uvaysov, Ilya Ivanov	Analysis of the Parasitic Parameters Influence on the Analog Filters Frequency Response
f256	Konstantin Klimov, Kirill Konov	Modification of the Integration Variable Selection Method in Numerical Simulation of Electromagnetic Wave Propagation in the Time Domain
f257	Vladimir P. Kulagin, Yuri M. Kuznetsov	Directions of development and creation of receiving demodulation modules for digital signal processing in communication systems

Seminar venue

Russian Science and Culture Centre in Prague,
Address : Na Zátorce str., 16



Spin-Dependent Tunneling in Semiconductor Structures Without an Inversion Center

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Abstract – The scientific article is devoted to a theoretical study of the tunneling of electrons through semiconductor barriers. It is shown that the tunneling process itself in such systems is spin-dependent and the transparency of the structures depends on the orientation of the electron spins even for symmetric barriers in the absence of an external magnetic field. The microscopic nature of this effect consists in the spin-orbit splitting of electronic states in the barrier, which is cubic in the wave vector. The actuality of the article is considering the theory of spin-dependent tunneling for single barriers and for resonant two-barrier structures. It is shown that the dependence of the tunnel transparency of the structures on the mutual orientation of the spin and the electron wave vector can be used for spin injection and for the electrical detection of the spin state of electrons. The influence of the spin-orbit interaction on the tunneling passage of charge carriers through non-centrosymmetric semiconductor barriers can manifest itself during the injection of free charge carriers from ferromagnets into a semiconductor through a potential barrier. The scientific novelty lies in the fact that, in the study of tunneling magnetoresistance in the structure of Fe/GaAs/Au, an anisotropic dependence of resistance on the magnetization of the Fe layer in the interface plane was found. Model calculation of the injection of electrons from Fe to Au through a semiconductor barrier GaAs taking into account the effect, enabled to explain the anisotropy observed experimentally.

Key words: potential barriers, tunneling, electronic spin, wave vector, spin-dependent phenomena, spin-orbit splitting, two-barrier structures, magnetoresistance.

INTRODUCTION

Spin-dependent tunneling phenomena physics has recently attracted much attention and has been investigating the injection of spin-oriented charge carriers from magnetic materials into semiconductor structures [1-3]. Spin injection (transfer of particles with non-equilibrium spin polarization) can be carried out in an external magnetic field in structures with spatial inhomogeneity of the effective q-factor. In this case, particles from one region of the structure with an equilibrium spin polarization determined by Zeeman splitting turn out to be equilibrium polarized along the spin, falling into the structure region with a different Zeeman splitting value. Injection of electrons with a no equilibrium spin due to a jump of q-factor at the interface of the contact and semiconductor, was first observed in n-type InSb by nuclear magnetic resonance by the change in the spin polarization of nuclei. It was shown later that the efficiency of such a spin injection method significantly increases with the transfer of charge carriers from a semimagnetic semiconductor layer, in which, due to the giant Zeeman splitting effect, free carriers are significantly polarized in spin in weak magnetic fields. This makes it possible to record the spin orientation of injected charge carriers by optical methods using photo or electroluminescence polarization, which has been demonstrated for various semiconductor compounds. The possibility of injection of spin-oriented electrons from semi-magnetic CdMnTe into the bulk CdTe layer [4], from BeMnZnS to the GaAs/AlGaAs quantum well [5], and also from GaMnAs holes to the InGaAs/GaAs quantum well [6]. It was shown in [7] that effective controlled spin injection can be carried out using tunnel diodes based on semimagnetic semiconductors. In this case, the resonance structure acts as a spin filter: depending on the applied voltage and the external magnetic field, electron tunneling occurs through different spin levels, which are energy-shifted relative to each other due to Zeeman splitting. Such spin-dependent electron tunneling in an external magnetic field was studied for structures based on semi-magnetic ZnMnSe/BeTe and (Zn, Mn, Be) Se [8] semiconductors. It has recently been established that the difference between the effective q-factor of free electrons leads to a spin-dependent photoemission of electrons from the surface of semiconductors to vacuum. For the practical implementation of spin injectors that work effectively at room temperature, the use of ferromagnetic structures seems promising. The possibility of injection of spin-oriented charge carriers from a ferromagnet into a semiconductor is shown in [9]. Experimentally, spin injection from a ferromagnet was carried out by tunnel scanning microscopy methods in the works on the injection of electrons from a Ni needle onto the (110) surface of bulk GaAs [10]. The spin orientation of electrons on the GaAs surface was detected by the polarization of the luminescence. However, in layered heterostructures, the effective transfer of a spin through the ferromagnet – semiconductor interface could not be observed for a long time. It was pointed out in the theoretical work [10] that the fundamental reason for the low efficiency of spin injection in heterostructures is the strong difference in the conductivity of a ferromagnetic material and a semiconductor. It was shown in [11] that this problem could be solved if charge carrier injection is carried out through a tunneling barrier located between a ferromagnet and a semiconductor. This solution turned out to be very productive, and in the years to come there appeared publications which investigated spin injection into low-dimensional semiconductor structures from various ferrimagnets, including Fe, NiFe, CoFe and MnAs. Experimental results indicate that the degree of spin polarization of injected electrons reaches a few tens of percent at room temperature. Recently it has been shown that asymmetric tunnel barriers themselves based on nonmagnetic structures can be used as spin filters [12]. It has been shown that the Rashba spin – orbit interaction on nonequivalent interfaces of asymmetric structures leads to the dependence of the tunnel transparency of barriers on the orientation of electron spins even in the absence of an external magnetic field. Such an effect is possible only in asymmetric systems with resonant tunneling through two-barrier and three barrier structures [13;14].

I. TUNNELIG THROUGH A SINGLE BARRIER

It is convenient to begin the analysis of spin-dependent tunneling with the classical problem of the passage of particles through a single rectangular barrier. Consider electron tunneling with a wave vector $\mathbf{k}=\mathbf{k}_{//},\mathbf{k}_z$ over the potential barrier of height V_b and thickness *b*, grown from a semiconductor with a zinc blende grating along the crystallographic direction *z*//[001] (Fig.1), where $\mathbf{k}_{//}$ the component of the wave vector is in the interface plane, the normal component of the wave vector. The Hamiltonian describing the propagation of electrons in the conduction band in each layer of the heterostructure, in the approximation of the effective mass, takes the form

$$\hat{H}=-\frac{\hbar^2}{2m^*}\frac{\partial^2}{\partial z^2}+\frac{\hbar^2\mathbf{k}_{//}^2}{2m^*}+V(z)+\hat{H}_D, \qquad (1)$$

where m^* the effective mass, which may be different in different layers, $V(z)$ is the profile of the potential energy of electrons that is, created by the heterostructure, $V(z)=V_b$ in the barrier and $V(z)=0$ in the contact regions, $\hat{H}_D$ is the Hamiltonian of the spin-orbit interaction.

In semiconductors with a zine blende lattice, the spin-orbit splitting of the conduction band is cubic in the wave vector and is described by the Dresselhaus Hamiltonian [15]

$$\hat{H}_D=\gamma\left[\hat{\sigma}_x\mathbf{k}_x(\mathbf{k}_y^2-\mathbf{k}_z^2)+\hat{\sigma}_y\mathbf{k}_y(\mathbf{k}_z^2-\mathbf{k}_x^2)+\hat{\sigma}_z\mathbf{k}_z(\mathbf{k}_x^2-\mathbf{k}_y^2)\right], \qquad (2)$$

where γ the parameter characterizing the force of the spin-orbit interaction, $\hat{\sigma}_\alpha(\alpha=x,y,z)$ the Pauli parameters, *x*//[100], *y*//[010], *z*//[001] are the cubic axes of the crystal.

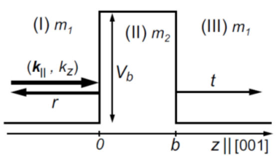


Fig.1. Electron tunneling with a wave vector through a rectangular potential barrier along the *z* axis

In the study of electron tunneling along the z axis, the component of the wave vector in equation (2) should be considered as an operator $-i\partial/\partial z$. We assume that the kinetic energy of the incident particles is much smaller than the height of the barrier V_b. In this case, the main contribution to the Hamiltonian of the spin-orbit interaction in the barrier $\mathbf{k}_z^2$ is determined by the equation

$$\hat{H}_D=\gamma(\hat{\sigma}_x\mathbf{k}_x-\hat{\sigma}_y\mathbf{k}_y)\frac{\partial^2}{\partial z^2}. \qquad (3)$$

The spin-orbit interaction (3) takes the form similar to the first term in the Hamiltonian (1), which describes the kinetic energy of an electron along the growth of the structure, and therefore can be considered as a spin-dependent correction to the effective electron mass in the direction of tunneling. Since the probability of particle tunneling through the barrier is determined, including by their mass, such an amendment leads to a dependence of the barrier transparency on the orientation of the electron spin. Hamiltonian (3) is diagonal zed by spinors

$$\chi_\pm=\frac{1}{\sqrt{2}}\begin{pmatrix}1\\ \mp e^{-i\varphi}\end{pmatrix}, \qquad (4)$$

which correspond to electronic states with opposite spin orientation. Here the polar angle of the wave vector is $\mathbf{k}=(\mathbf{k}_{//}\cos\varphi,\mathbf{k}_{//}\sin\varphi,\mathbf{k}_z)$.

II. SPIN ORRIENTATION DEPENDENCIES

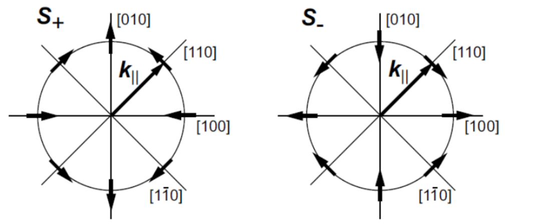
Particles in spin states $\chi_\pm$ propagate inside the barrier with preservation of the spin for various indicators of the attenuation of the wave function for the values of the parameter $\gamma>0$. Spatial orientations of electron spins in their own states $\chi_\pm$ depend on the direction of the wave vector $\mathbf{k}_{//}$ in the interface plane and determined by the equation

$$s_\pm=\pm\frac{1}{2}(-\cos\varphi,\sin\varphi,0). \qquad (5)$$

Fig.2 shows the orientation of the spins $s_\pm$ for different directions of the wave vector **k** (as a function of the polar angle φ). Electronic spins in their own states $s_\pm$ oriented along the wave vector $\mathbf{k}_{//}$, if vector $\mathbf{k}_{//}$ directed along the cubic axes of the crystal [110] or [010], and is perpendicular to the wave vector $\mathbf{k}_{//}$, if $\mathbf{k}_{//}$. We assume that the tunneling occurs without scattering processes. In this case, the component of the electron wave vector in the plane of the interfaces $\mathbf{k}_{//}$ is conserved, and particles with spins $s_\pm$ pass through the barrier with the spin conservation. In the basis of Eigen states $\chi_\pm$ Hamiltonian (1) with spin-orbit interaction (3) is diagonal along spin indices and takes the form

$$\mathbf{H}_{\pm} = -\frac{\partial^2 \hbar^2}{\partial z^2 2m_{\pm}} + \frac{\mathbf{k}_{//}^2 \hbar^2}{2m^*} + V(z), \qquad (6)$$

where $m_{\pm}$ is the effective mass of electrons along the growth axis of the structure, modified by the spin-orbit splitting of the conduction band, $m_{\pm} = m^*\left(1 \pm 2\frac{\gamma m^* \mathbf{k}_{//}}{\hbar^2}\right)^{-1}$.



Pic.2. Spin orientation dependencies $s_{\pm}$ from the direction of the electronic wave vector in the plane of the interfaces $\mathbf{k}_{//}$

Wave function of electrons in their own spin states $\chi_{\pm}$ in each layer of the heterostructure can be represented as

$$\Psi(r)_{\pm} = u(z)_{\pm} \chi_{\pm} \exp(i\mathbf{k}_{//}\rho), \qquad (7)$$

where $\rho = (x, y)$ coordinate n the interface plane.

The function $u_{\pm}(z)$, describing the sum of the incident and reflected wave in region I and the wave in region III (Fig.1), takes the from

$$\begin{cases} u_{\pm}^{(\mathrm{I})}(r) = \exp(i\mathbf{k}_z z) + r_{\pm}\exp(-i\mathbf{k}_z z); \\ u_{\pm}^{(\mathrm{II})}(r) = A_{\pm}\exp(\mathbf{q} \pm z) + B_{\pm}\exp(-\mathbf{q} \pm z); \\ u_{\pm}^{(\mathrm{III})}(r) = t_{\pm}\exp(i\mathbf{k}_z), \end{cases} \qquad (8)$$

where $r_{\pm}; t_{\pm}$ are the amplitude transmission and reflection coefficients of particles with spin $s_{\pm}, \mathbf{q}_{\pm}$ are the indicators of wave functions in the barrier,

$$\mathbf{q}_{\pm} = \mathbf{q}_0\left(1 \pm 2\frac{\gamma m_2 \mathbf{k}_{//}}{\hbar^2}\right)^{-1/2}; \qquad (9)$$

$$\mathbf{q}_0 = \sqrt{\frac{2m_2 V_b}{\hbar^2} - \mathbf{k}_z^2 \frac{m_2}{m_1} - \mathbf{k}_{//}^2\left(\frac{m_2}{m_1} - 1\right)}$$

the attenuation coefficient of the wave function without taking into account the spin-orbit interaction, m_1 and m_2 are the effective masses in the contact regions and inside the barrier. The use of boundary conditions at the interfaces allows writing a closed system of linear equations and coefficients $t_{\pm}, r_{\pm}, A_{\pm}, B_{\pm}$ and determine the dependence of the transmission and reflection coefficients on the orientation of the electron spins. Since we are interested in spin tunneling due to the splitting of the electron spectrum in the barrier, we will use standard boundary conditions for the continuity of the wave function $\psi_{\pm}$ and flow $(1/m_{\pm})\partial\psi_{\pm}/\partial z$ at heterojunctions. In addition, we will neglect the spin-orbit interaction in the contact layers I and III, since the spin splitting due to cubic in $\mathbf{k}_{//}$ terms in these regions is small. The calculation shows that the transmission coefficients $t_{\pm}$ for compounds with moderate spin-orbit interaction $\gamma m_2 \mathbf{k}_{//}/\hbar^2 << 1$ and sufficiently wide $\exp(-b\mathbf{q}_0) << 1$ barriers have the form [15]

$$t_{\pm} = t_0 \exp\left(\pm\gamma\frac{m_2 \mathbf{k}_{//}}{\hbar^2}\mathbf{q}_0 b\right); \qquad (10)$$

$$t_0 = -4i\frac{m_2 \mathbf{k}_z \mathbf{q}_0}{m_1(\mathbf{q}_0 - i\mathbf{k}_z m_2/m_1)^2}\exp(-\mathbf{q}_0 b - i\mathbf{k}_z b)$$

the transmission coefficient calculated without taking into account the spin-orbit splitting of the spectrum. The general problem of the passage of electrons with an arbitrary initial spin orientation set by a spinor χ through a barrier based on a semiconductor with a zinc blende grating can be solved by decomposing the Hamiltonian (3) into proper spin states $\chi_{\pm}$. To analyze spin-dependent tunneling, it is convenient to introduce the polarization efficiency of the structure [14;15]

$$P = \frac{|t_+|^2 - |t_-|^2}{|t_+|^2 + |t_-|^2}, \qquad (11)$$

which describes the relative difference in the probabilities of passing the barrier by particles with spins $s_{\pm}$. Substituting the transmission coefficients (10) into (12) leads to the following equation for the polarization efficiency of a single barrier

$$P = \mathrm{th}\left(2\gamma\frac{m_2 k_{//}}{\hbar^2}q_0 b\right). \qquad (12)$$

CONCLUSION

For a fixed value of the longitudinal wave vector $\mathbf{k}_{//}$, the polarization efficiency of the tunnel structure increases with increasing spin-orbit coupling constant γ and barrier thickness *b*. To achieve higher polarization efficiency values, thick barriers must be used. It should be noted that an increase in the barrier thickness leads to a significant decrease in its transparency and, consequently, to a decrease in the tunneling flux of electrons. The calculation results indicate that the polarization efficiency can reach several percent for reasonable barrier thicknesses. Structures based on the GaSb compound and its solid solutions are the most effective spin filters due to the large value of the product γm^* in these materials.

REFERENCES

[1] R.H. Silsbee, “Spin orbit induced coupling of charge current and spin polarization,” J. Phys.: Condens. Matter., vol. 16, 2004, p.179.

[2] M. Oestreich, P.J. Klar, W. Heimbrodt, D.E. Ashenford, “Spin injection into semiconductors,” Appl. Phys. Lett., vol. 74, 1999, p.1251.

[3] R. Fiederling, M. Keim, G. Reuscher, W. Ossau, G. Schmidt, “In-

jection and detection of a spin-polarized current in a light emitting diode," Nature (London), vol. 402, 1999, p.787.

[4] Th. Gruber, M. Keim, R. Fiederling, G. Reuscher, W. Ossau, G. Schmidt, "Electron spin manipulation using semi magnetic resonant tunneling diodes," Appl. Phys. Lett., vol. 78, 2001, p.1101.

[5] S.F. Alvarado, "Observation of spin-polarized-electron tunneling from a ferromagnetic into GaAs," Phys. Rev. Lett., vol. 68, 1992, p.1387.

[6] V.P. Labella, D.W. Bullock, "Spatially resolved spin-injection probability for gallium arsenide," Science, vol. 292, 2001, p.1518.

[7] E.I. Rashba, "Theory of electrical spin injection: Tunnel contacts as a solution of the conductivity mismatch problem," Phys. Rev., vol. B62, 2000, p.16267.

[8] H.J. Zhu, M. Ramsteiner, H. Kostial, M. Wassermeier, H.-P. Schonherr, K.H. Ploog, "Room-temperature spin injection from Fe into GaAs," Phys. Rev. Lett., vol. 87, 2001, p.016601.

[9] P.R. Hammar, M. Johnson, "Spin-dependent current transmission across a ferromagnetic insulator two-dimensional electron gas junction," Appl. Phys. Lett., vol. 79, 2001, p.2591.

[10] A. Hanbicki, O.M.J. Van Erve, R. Magno, G. Kioseoglou, C.H. Li, B.T. Jonker, G. Itskos, R. Mallory, "Analysis of the transport process providing spin injection through an Fe/AlGaAs," Schottky barrier, Appl. Phys. Lett., vol. 82, 2003, p.4092

[11] V.F. Motsnyi, J. De Boeck, J. Das, W. Van Roy, G. Borghs, "Electrical spin injection in a ferrimagnet/tunnel barrier/semiconductor heterostructure," Appl. Phys. Lett., vol. 81, 2002, p.265.

[12] N.N. Chernyshov, A.A. Slusarenko, "Study the photovoltaic effect in the spin resonance for crystals without inversion centre," Zbior artykulow naukowych / Inzynieria i technologia. Nauka wczoraj, dzis, jutro; Warszawa, 02.2016, pp.53-58.

[13] N.N. Chernyshov, "Conductivity of multicomponent electron gas," Radio electronics & informatics," vol. 1; KhNURE, 2015, pp.23-25.

[14] J. Moser, A. Matos-Abiague, J. Fabian, "Tunneling anisotropic magnetoresistance and spin-orbit coupling in Fe/GaAs/Au tunnel junctions," Phys. Rev. Lett., vol. 99, 2007, p.056601.

[15] G. Dresselhaus, "Spin-orbit coupling e_ects in zinc blende structures," Phys. Rev., vol. 100, 1955, p.580.