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LETTERS

Nanoelectronics and nanotechnology: promising approaches in the educational process

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Abstract
Objectives. Nanoelectronics is concerned with the development of physical and technological foundations for the creation of integrated circuits comprised of elements whose topological dimensions do not exceed 100 nm. Nanotechnology includes the creation and use of materials, devices and technical systems whose functioning is determined by their nanostructure, i.e., comprising ordered fragments ranging from 1 to 100 nm in size. The present research is aimed at developing a concept for training highly qualified specialists in the field of nanoelectronics and nanotechnologies on the example of the Department of Nanoelectronics of the Institute of Advanced Technologies and Industrial Programming at the MIREA – Russian Technological University.
Methods. Promising approaches for supporting the educational process within the nanoindustry are analyzed and compared.
Results. Three fundamental components of education in the field of nanoindustry can be distinguished: physical (the study and search for new promising physical effects); materials science, related to the study, search, and synthesis of new advanced materials; informatics (including mastering of modern software packages and programming languages for modeling a wide range of nanoindustry elements and materials).
Conclusions. All three fundamental components of education within nanoindustry have been effectively implemented by combining scientific laboratories and centers at the Department of Nanoelectronics. After graduating from the Department of Nanoelectronics, graduates can work for leading scientific institutes and technical organizations in Russia, intern at specialized organizations in neighboring and other countries, teach at leading universities, and start their own knowledge-intensive business.

Keywords: nanoelectronics, nanotechnology, education

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ПИСЬМО В РЕДАКЦИЮ

Наноэлектроника и нанотехнологии: перспективные подходы в образовательном процессе

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Резюме
Цели. Наноэлектроника – область современной электроники, занимающаяся разработкой физических и технологических основ создания интегральных схем с характерными топологическими размерами элементов, не превышающими 100 нм. Нанотехнологии включают создание и использование материалов, устройств и технических систем, функционирование которых определяется наноструктурой, то есть ее упорядоченными фрагментами размером от 1 до 100 нм. Цель работы – раскрыть концепцию подготовки высококвалифицированных специалистов в сфере наноэлектроники и нанотехнологий на примере кафедры наноэлектроники Института перспективных технологий и индустриального программирования РТУ МИРЭА.
Методы. Анализ перспективных подходов в образовательном процессе в рамках наноиндустрии.
Результаты. В статье выделены три фундаментальные составляющие образования в сфере наноиндустрии: физическая (изучение и поиск новых перспективных физических эффектов); материаловедческая, связанная с изучением, поиском и синтезом новых перспективных материалов; информационная (освоение современных пакетов программ и языков программирования для моделирования широкого спектра элементов и материалов наноиндустрии).
Выводы. Сочетание научных лабораторий и центров на кафедре наноэлектроники позволило эффективно реализовать все три фундаментальные составляющие образования в сфере наноиндустрии. После окончания кафедры наноэлектроники выпускники могут работать в ведущих институтах и научно-технических организациях России, стажироваться в организациях ближнего и дальнего зарубежья, преподавать в ведущих вузах и создавать собственные наукоемкие предприятия.

Ключевые слова: наноэлектроника, нанотехнологии, образование

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INTRODUCTION

Nanoelectronics is a field of modern electronics aimed at developing the physical and technological foundations for integrated circuits comprised of elements whose characteristic topological dimensions do not exceed 100 nm. For elements having such dimensions, the increasingly dominant role played by quantum effects starts to become a fundamentally important issue. Electronic devices that use such quantum effects form the basis of emerging nanoheterostructural electronics. In this connection, the following primary objectives of nanoelectronics may be distinguished: 1) developing the physical foundations for operation of nanoscale devices, especially quantum devices; 2) developing the necessary physical foundations for technological processes; 3) developing the devices themselves along with the relevant manufacturing technologies; 4) developing nanoscale integrated circuits and electronic products based on a nanoelectronics element base [1, 2].

Although representing a relatively new direction in science and technology, nanotechnology has been under active development in recent decades. Nanotechnology involves the creation and utilization of materials, devices, and technical systems whose function is determined by their nanostructure, that is, by their ordered fragments ranging from 1 to 100 nm. The term "nano" comes from the Greek word "nanos," meaning "dwarf." One nanometer (nm) is one billionth of a meter or 10 Å. The term "nanotechnology" was defined in 1974 by Norio Taniguchi, Professor of Materials Science at Tokyo Science University as "production technology to get extra high accuracy and ultrafine dimensions … on the order of 1 nm…" [1].

Nanoindustry opens up wide horizons and a range of opportunities in many industries and national economy including, but not limited to, the following:

- nanoelectronic and nanophotonic elements (semiconductor transistors and lasers, photodetectors, solar cells, and various sensors);
- ultra-dense data recording devices;
- telecommunications, information, and computing technologies; supercomputers;
- video equipment (flat screens, monitors, and video projectors);
- molecular electronic devices including switches and electronic circuits at the molecular level;
- nanolithography and nanoimprinting;
- fuel cells and energy storage devices; micro- and nanomechanical devices including molecular motors, nanomotors, and nanorobots;
- nanochemistry and catalysis including combustion control, coating process, electrochemistry, and pharmaceuticals;
- aerospace and defense applications; environmental monitoring devices;
- targeted drug and protein delivery, biopolymers and biological tissue healing, clinical and medical diagnostics, creation of artificial muscles and bones, and implantation of living organs;
- biomechanics;
- genomics;
- bioinformatics;
- bioinstrumentation;
- registration and identification of carcinogenic tissues, pathogens, and biologically harmful agents;
- safety in agriculture and food production.

While recent advances in nanoelectronics and nanotechnology are especially applicable to the defense industry, the nanoindustry continues to expand into new areas of science, techniques, and manufacture with the discovery of new physical effects and the synthesis of promising materials. Therefore, the training of highly qualified specialists in nanoindustry becomes an important task in the contemporary world [2].

PROMISING APPROACHES TO NANOINDUSTRY EDUCATION AT THE DEPARTMENT OF NANOELECTRONICS

At MIREA – Russian Technological University (RTU MIREA), specialists in nanoelectronics and nanotechnologies are trained in the Department of Nanoelectronics of the Institute of Advanced Technologies and Industrial Programming. Currently, there are two areas of training: 11.03.04 "Electronics and nanoelectronics" and 28.03.01 "Nanotechnologies and microsystems engineering." RTU MIREA is the only Russian higher education institution awarded the 2017 UNESCO Medal for its contributions to the development of nanoscience and nanotechnologies. The award was given, among other things, for excellence in training students in this area. Educational programs related to nanoelectronics and nanotechnologies are implemented by the Department of Nanoelectronics.

Within the 11.03.04 "Electronics and nanoelectronics" program, students are educated in modern technologies, materials and electronic products, as well as the design and use of electronic devices and appliances. In addition, they acquire knowledge and professional skills in conducting theoretical and experimental research, computer modeling, design, engineering, manufacture engineering, use and application of materials, components, electronic instruments and devices, and vacuum, plasma, solid-state, microwave, optical, micro- and nanoelectronic devices with various functionalities and purposes.

The program subjects are:

- Electronics and microprocessor technology;
- Fundamentals of electronic component platform design;
- Computer-aided design in electronics;
- Electronic materials and equipment;
- Electronic component platform technologies;
- Advanced technological processes of micro- and nanoelectronics;
- Nanoelectronics;
- Physics of low-dimensional structures;
- Condensed matter physics;
- Quantum mechanics and statistical physics;
- Research management.

Within the 28.03.01 "Nanotechnologies and microsystems engineering" program, the area of professional activity comprises theoretical and experimental research, mathematical and computer modeling, design, manufacture engineering and application of materials, instruments and devices of nano- and microsystems engineering having various functionalities and purposes, as well as the development and application of nanotechnology processes and nanodiagnostic methods. Students study materials and devices of nano- and microsystems engineering, units and appliances based on them, nanoelectronics technology and nanodiagnostic methods, as well as equipment for synthesis processes, diagnostics and testing of materials and components of nano- and microsystem materials and components.

The program subjects are:

- Experiment planning, data processing and interpretation;
- Physical principles of nanotechnology and microsystems engineering;
- Quantum mechanics and statistical physics;
- Condensed state physics;
- Micro- and nanosystem diagnostics and analysis methods;
- Modeling and design of micro- and nanosystems;
- Materials science and processes of nanostructured material production;
- Micro- and nanosystem devices;
- Advanced nanomaterials;
- Structure of materials;
- Research management.

In the present job market, the greatest chances for career success are enjoyed by specialists who are not only versed in modern technology, but who also have a grounding in the fundamental sciences; this is likely to become an even more pronounced trend in the future. Here, physics, which forms the primary basis of new high technologies, is increasingly penetrating into other applied sciences. There is particular interest in quantum physics, due to forming the basis for nanotechnology and the creation of new devices and appliances in nanoelectronics. Here, the concept of the so-called “quantum computer” capable of revolutionizing informatics and communications may serve as an example. The ability of physicists to quickly retrain and master new disciplines is highly valued. Many young specialists who have received a good physics education work successfully not only in science and production but also in economics and business.

The contemporary nanoindustry is characterized by the search for new materials with promising properties that simultaneously permit the miniaturization of nanoelectronic devices and increased response speed of their elements. Moreover, the development of nanosystems is fundamentally dependent on modern computer technologies for analyzing large amounts of complex data.

Thus, three fundamental components of education in nanoindustry can be distinguished: physical (the study of and search for new promising physical effects); materials science related to the study, search, and synthesis of new advanced materials; and informative (including mastering of modern software packages and programming languages for modeling a wide range of nanoindustry elements and materials).

At the Department of Nanoelectronics, sufficient time is devoted to all three components while implementing educational programs. The training process is carried out in departmental laboratories, including the specialized training and scientific Superfast Ferroic Dynamics and Nanotechnology Femtosecond Optics laboratories. These laboratories carry out the following educational and scientific activities:

- training students and postgraduates to use modern laser equipment;
- conducting research in superfast dynamics of ferroic materials for micro-, opto-, and nanoelectronics;
- research in the field of terahertz radiation;
- development of elements and devices for modern electronics;
- research in the field of nanomaterials and nanosystems for two-dimensional electronics.

Many lecturers of the department are also the members of the research staff of RTU MIREA scientific centers, such as the Magnetoelectric Materials and Devices research and educational center (REC), the Integrated Circuits, Nanoelectronics Devices and Microsystems Design Center, the Research Institute of Solid-State Electronics Materials, and the Technology Center.

The following educational and scientific activities are carried out at the Magnetoelectric Materials and Devices:

- training students to operate modern measuring equipment;
- conducting research in the field of magnetism and ferroelectricity;
- studying magnetoelectric effect, magnetostriction;
- developing modern nanoelectronic devices and appliances.

The main activity areas of the Integrated Circuits, Nanoelectronics Devices and Microsystems Design Center are:

- education, training, retraining, and advanced training of specialists in the field of integrated systems for computer-aided design of electronic component platform and devices;
- design of very large scale integration systems, “systems-on-a-chip”, and “systems-in-package”;
- research on methodology of computer-aided design based on the development of theory and practice of system abstraction layer for describing integrated circuits;
- modeling and development of new devices and instruments of microsystems engineering;
- implementation of integrated circuit prototypes and design of electronic modules based on programmable

logic circuits, and development of control and measuring systems with various functionalities and purposes;
- instrumental and technological modeling of new microwave solid-state electronics devices based on AlGaN nanoheterostructures.

The Research Institute of Solid-State Electronics Materials carries out activities in the following areas:
- training students to work with modern equipment (laboratory work);
- conducting research in the field of condensed state physics and solid-state electronics;
- research of optical, structural, and magnetic properties of modern materials and elements of electronics;
- research in the field of nanomaterials and nanosystems for modern electronics.

The Technology Center REC is active in research and training in the following technologies:
- technologies of dielectric thin films and nanostructures, including active dielectrics;
- film-forming solutions and methods for the formation of ferroelectric heterostructures (PZT[1], BST[2], etc.);
- film-forming solutions and methods for the formation of porous insulating dielectrics with low dielectric constant (low-k) using molecular self-assembly methods;
- film-forming solutions for producing various oxides (Si, Ti, Zr, etc.) and inorganic-organic hybrids;
- planarization in BEOL[3] and FEOL[4] processes;
- segnetoelectric thin films, hetero- and nanostructures, and composites;
- CSD[5] and ALD[6] technologies.

In addition to activities carried in RTU MIREA laboratories and research centers, students undergo practical training, participate in R&D, and carry out their final qualification works at a wide range of partner enterprises and universities, which are also their potential employers. Such organizations include: Roselektronika, NPP Pulsar, Pluton, NPP TORII, MICRON, the Institute of Physics and Technology of Russian Academy of Sciences (RAS), Lomonosov Moscow State University, National Research Center "Kurchatov Institute," Central Research and Technology Institute "Tekhnomash," I.P. Bardin Central Research Institute for Ferrous Metallurgy, and many others.

[1] PZT is lead zirconate titanate, chemical formula $Pb[Zr_xTi_{1-x}]O_3$ $(0 \le x \le 1)$.

[2] BST is barium strontium titanate, chemical formula $Ba_{1-x}Sr_xTiO_3$ $(0 \le x \le 1)$.

[3] BEOL (back end of line) is the second portion of IC fabrication.

[4] FEOL (front end of line) is the first portion of IC fabrication.

[5] CVD is chemical vapor deposition of coatings.

[6] ALD is atomic layer deposition.

Along with the corresponding postgraduate programs, the Department of Nanoelectronics offers bachelor's and master's degrees, i.e., there is a full educational cycle in areas related to nanotechnology and nanoelectronics.

Students and graduate students of the Department of Nanoelectronics are actively published in leading international journals (indexed in Web of Science and Scopus) including Q1 journals [3–6] and in leading Russian journals (included in the List of the peer-reviewed science press of the State Commission for Academic Degrees and Titles of the Russian Federation), present their work at international and national conferences, become winners and medalists of all-Russian and international competitions, and receive grants, including megagrants.

A significant personal contribution to the training and development of the department, the institute, and the entire RTU MIREA is made by teachers, who are also leading scientists and specialists in their field. Here, we would especially like to remember those who, unfortunately, are no longer with us. The loss of Aleksander Igorevich Morozov is especially poignant: Professor, Doctor of Physical and Mathematical Sciences, RTU MIREA Vice-Rector for Science, a remarkable teacher and author of a large number of scientific works (in particular, [7–9]). The scientific group led by Professor A.I. Morozov has predicted a new type of domain walls formed by frustrations in these nanostructures, as well as constructing their magnetic phase diagram. The contribution of "unusual" domain walls to the giant magnetoresistance has been calculated. Professor Vladimir Georgievich Morozov, Doctor of Physical and Mathematical Sciences, is one of the world's leading experts in nonequilibrium thermodynamics, the author of the two-volume book "Statistical Mechanics of Nonequilibrium Processes" being in demand among professionals, and a remarkable teacher and methodologist. We should also mention Vladimir Fyodorovich Meshcheryakov, Doctor of Physical and Mathematical Sciences, a leading specialist in the field of electron paramagnetic resonance, Andrei Fyodorovich Volkov, Doctor of Physical and Mathematical Sciences, Professor, and Iosif Grigorievich Yerusalimchik, Doctor of Chemical Sciences, Professor, as well as Boris Vladimirovich Magnitskii and Aleksandr Borisovich Romanov, associate professors. All of them have devoted their lives to training highly qualified specialists. Their students continue to work and teach at the Department today.

At present, active scientific work is carried out by scientific groups under the leadership of A.S. Sigov, Academician of the RAS, Professors E.D. Mishina, Y.K. Fetisov and L.Y. Fetisov, A.A. Bush, V.S. Pokatilov, K.A. Vorotilov, V.I. Kapustin, M.S. Blanter, A.N. Yurasov, Associate Professor E.F. Pevtsov [10–20].

CONCLUSIONS

In conclusion, we note that all fundamental components of education in the field of nanoindustry are effectively implemented by taking a balanced approach of combining scientific laboratories and centers in the university structure. Graduates of the Department of Nanoelectronics have many and varied career opportunities, including:

- teaching and research work in leading national universities;
- working for Russian scientific and technical institutions;
- traineeship and work in specialized institutions in neighboring and other countries;
- starting their own knowledge-intensive business.

Authors' contributions

A.S. Sigov—conceptualization, description of the methodology, and editing the text of the article.

I.V. Gladyshev—data curation, conducting research.

A.N. Yurasov—the main idea, data curation, conducting research, writing and editing the text of the article.

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