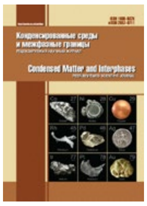

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90 years of the scientific school of solid state physics at Voronezh State University: from solid state physics to nanophysics (Scientific and historical essay)

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Abstract

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Для цитирования: Домашевская Э. П. 90 лет научной школе физики твердого тела Воронежского государственного университета: от физики твердого тела до нанофизики (Научно-исторический очерк). *Конденсированные среды и межфазные границы*. 2025;27(3): 497–517. https://doi.org/10.17308/kcmf.2025.27/13024

Foundation of the scientific school in Voronezh

The emergence of solid state physics at Voronezh State University is associated with the outstanding personality of Maria Afanasyevna Levitskaya, one of the first female physicists in Russia and the Soviet Union, a comrade-in-arms and colleague of the famous academician Abram Fedorovich Ioffe. M. A. Levitskaya was invited in 1935 by VSU Rector Norin A.Ya to head first the Department of Theoretical Physics at the Physics and Mathematics Department, and then (1937) the Department of Electromagnetic Oscillations that she created. Thus, in 1935, in connection with the appearance at VSU of the famous professor M. A. Levitskaya, became the beginning of the development of modern fundamental physical trends and scientific schools in Voronezh, and above all, a scientific school in the field of solid state physics.

Maria Afanasyevna received an excellent education, first in St. Petersburg at the Physics and Technology Department of the Higher Women's Bestuzhev Courses (1901–1904), the last two semesters of which she completed at the University of Berlin (1905-1906), where she specialized under the scientific supervision of the founders of quantum physics Max Planck and Paul Drude. Then in 1911-1914 she completed an internship in Göttingen and Holland [1–4]. After returning from Europe, Maria Afanasyevna worked for about twenty years (1923–1934) at the Leningrad Physico-Technical Institute at the invitation of its first director, Academician Abram Fedorovich Ioffe, carrying out the first research in solid state physics with him, and headed the Ultrashort Wave Department. It is interesting that the Academic Council of this institute, which included academicians I. V. Kurchatov, A. P. Aleksandrov, N. N. Semenov, and Ya. I. Frenkel, who later became famous throughout the world, included only one woman – M. A. Levitskaya. Fig. 1 shows a 1927 photograph of the staff of the Leningrad Physico-Technical Institute of the USSR Academy of Sciences, headed by the director, Academician A. F. Ioffe.

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Fig. 1. The collective of the Leningrad Physico-Technical Institute LPTI of the USSR Academy of Sciences headed by the director Academician A. F. Ioffe in 1927

With her main discovery of submillimeter waves, M. A. Levitskaya proved the unity of the electromagnetic nature of radio waves and light in a single scale of electromagnetic oscillations, independently and almost simultaneously with another female physicist, Alexandra Andreevna Glagoleva-Arkadyeva [5]. In 1909, in the Journal of the Russian Physical Society, M. A. Levitskaya published her first original study, "Radiation of a Rectilinear Resonator in the Region of Short Electromagnetic Waves."

In the early thirties, after the publication of the unique monograph "Infrared Rays" [6], M. A. Levitskaya was awarded the academic degree of Doctor of Physical and Mathematical Sciences "for outstanding scientific achievements" without defending her dissertation, following I. V. Kurchatov.

This is the background to the emergence and development of modern scientific physical schools at the Voronezh State University, including the scientific school of solid state physics. Already in the post-war period of restoration of science and education since 1961, the Department of Electromagnetic Oscillations began to be called the Department of Solid State Physics, after several other departments that originated in its depths separated from the large system-forming Department of Electromagnetic Oscillations, including the Department of Radiophysics and the Department of Optics and Nuclear Physics. Why did the remaining basic department begin to be called the Department of Solid State Physics since 1961? The fact is that M. A. Levitskaya, together with A. F. Ioffe, stood at the origins of the then emerging physics of solid state in the 1920s and 1930s, studying the electromechanical and deformation properties of classical solids, single crystals of rock salt and quartz, using X-ray methods, which they mastered in Germany from the great scientist Wilhelm Conrad Roentgen, who discovered X-rays in November 1895, called X-rays only in Russia and Germany. In English-speaking countries, this radiation is still called X-rays. In 1903–1906, A. F. Ioffe completed an internship at the University of Munich with Nobel Prize Laureate (1901) V. K. Roentgen, carrying out work on the mechanical and electrical properties of crystals.

When Maria Afanasyevna, together with A. F. Ioffe, began studying the mechanical properties of single crystals, Max Born had already published the general theory of crystal lattices (1916). The Born's electrostatic theory correctly described a number of properties of single crystals, could not, however, explain some of the observed phenomena. For example, a sample of crystalline rock salt NaCl breaks under a stress of 0.4 kg/mm, whereas according to theoretical estimates it should be 200 kg/mm^2. According to this theory, the same crystal should have high elastic properties regardless of the loads applied to it. Meanwhile, in practice, a transition from elastic to plastic deformation is observed, often caused by small external forces. Experimenters could answer all these questions only by looking inside the substance. This opportunity was provided to experimental physicists by the famous X-rays discovered by Roentgen in 1895 and their diffraction on NaCl single crystals, discovered by his students led by Laue in 1912.

It was around these years (1911–1914) that Maria Afanasyevna was doing an internship at the University of Göttingen in Germany. Returning to Russia, she and A. F. Ioffe began to successfully apply X-ray methods in studies of the mechanical properties of crystals. First of all, the young scientists began to clarify the nature and laws of plastic deformation using NaCl as an example. By recording Lauegrams from NaCl single crystals subjected to continuous mechanical action (compression or stretching), scientists discovered and studied in detail the phenomena of asterism in the form of spot multiplication on the Lauegram after passing a certain limit of load on the crystal, i.e. the elastic limit. In this case, plastic deformation occurs in the crystal, as a result of which the single crystal is subjected to destruction into separate blocks sliding along a certain crystallographic plane relative to each other. In her subsequent works, Maria Afanasyevna proved the role of surface microcracks (defects) in reducing the ultimate strength of crystals compared to the theoretical one. A decrease in their number when dissolved in water led to an increase in tensile strength by 10-100 times and brought it closer to the theoretical limit. Based on the results of these works, in 1924 the work of A. F. Ioffe, M. V. Kirpicheva and M. A. Levitskaya "Deformation and Strength of Crystals" [7] was published in the "Journal of the Russian Physical-Chemical Society", which is still referred to today.

Therefore, at the Department of Solid State Physics of Voronezh State University, from its very foundation, X-ray methods were established and developed as the main methods for studying solids and various materials - X-ray diffraction (XRD) and X-ray spectroscopy (XRS), which make it possible to obtain data on the atomic structure and electron-energy spectrum of matter, respectively. Under the supervision of Professor M. A. Levitskaya, XRD studies of metals and alloys, and then semiconductors, were carried by N. A. Ignatiev, R. L. Fogelson and aspirants N. A. Vodopyanova, K. B. Aleynikova. XRS research methods were used in their research by V. S. Kavetsky, I. I. Kapshukov and one of the last aspirants of M. A. Levitskaya, E. P. Domashevskaya.

In the post-war years, Maria Afanasyevna and her student E. A. Kuznetsova conducted XRD studies of second-row stresses in thin layers of rock salt (and aluminum) obtained by evaporation in a vacuum. At the same time, together with her aspirants R. L. Fogelson and N. A. Vodopyanova, Maria Afanasyevna created an XRD method for studying diffusion in metals. This method for determining diffusion coefficients found its greatest development in the works an associate professor R. L. Fogelson. The values of diffusion coefficients for many metals obtained by him were included in international reference books of the US National Bureau of Standards.

X-ray spectroscopy did not go unnoticed by Maria Afanasyevna either. Aspirants V. S. Kavetsky (future dean of the Physics Department), I. I. Kapshukov and E. P. Domashevskaya (future head of the Solid State Physics Department) were involved in research in this area. After the war, M. A. Levitskaya was the only professor of physics in Voronezh. But already on May 15, 1945, at a scientific session of VSU, Maria Afanasyevna made her first post-war report on tellurium radiation.

During the Great Patriotic War and the post-war period, M. A. Levitskaya studied the structure of atomic nuclei, β-decay, diffusion issues in solids, explored X-ray spectra of alloys and intermetallic compounds, optical spectra of thin metal layers (Fig. 2). Together with the German professor Robert Dopel, interned in Voronezh after the war, he organized a laboratory of nuclear spectroscopy at VSU, and then in 1959 he organized the Department of Nuclear Physics and became its first head, simultaneously heading the Department of Electromagnetic Oscillations. The results of M.A. Levitskaya's research were published in more than 50 articles, in the monograph "Infrared Rays" and the last unpublished manuscript "Vortex Model of the Nucleus".

From the newspaper "Kommuna" for March 9, 1960: "... Decree of the Presidium of the Supreme Soviet of the USSR of March 7, 1960. *"In commemoration of the 50th anniversary of International Women's Day and noting the active*

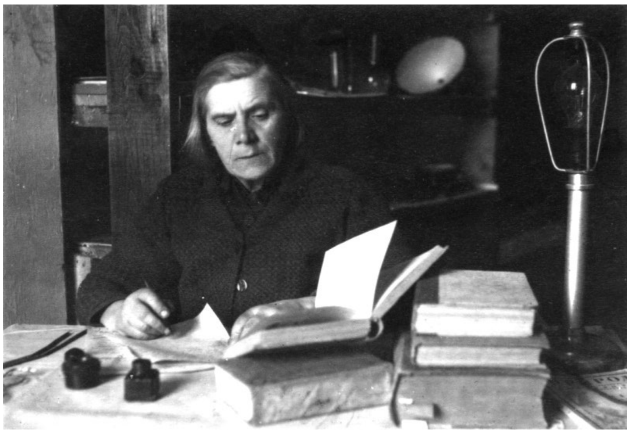

Fig. 2. Maria Afanasyevna Levitskaya in the laboratory of the Electromagnetic Oscillations Department in the post-war years (Red Building of VSU on Prospekt Revolyutsii, 24)

Fig. 3. The Order of the Red Banner of Labor - an award to M. A. Levitskaya in 1960

*participation of women of the Soviet Union in communist construction and their services to the Soviet state in educating the younger generation, for achieving high labor performance and fruitful social activities, to award ... the Order of the Red Banner of Labor to Professor Maria Afanasyevna Levitskaya, head of the Department of Electromagnetic Oscillations at Voronezh State University... "(*Fig. 3).

Thus, M.A. Levitskaya became the founder of the largest scientific school of physics in Voronezh, which currently includes more than 50 doctors of science.

Achievements of the scientific school in the field of semiconductors

The stimulus for the further development and growth of the Voronezh scientific school of solid state physics at VSU was active research into the electronic structure of semiconductor compounds associated with the rapid development of semiconductor physics. Since the middle of the last century, in connection with Schottky's discoveries of the rectifying properties of a metal-semiconductor heterocontact, a real boom in the field of synthesis of new semiconductor compounds and materials suitable for use in various fields of technology, and above all, in electronics and optoelectronics. Academician A. F. Ioffe, who headed the Physico-Technical Institute of the USSR Academy of Sciences in Leningrad for several decades, did not escape this boom. Single crystals of numerous semiconductor compounds of various types ($A^{III}B^{V}$, $A^{II}B^{VI}$, $A^{II}B^{IV}C^{V}_2$) were synthesized and studied at the Physico-Technical Institute. The leadership in these studies in the USSR belonged to Nina Aleksandrovna Goryunova, the founder of a new scientific direction – the chemistry of complex diamond-like semiconductors [8], laureate of the N. S. Kurnakov Prize of the USSR Academy of Sciences, Cavalier of the Order of Lenin. She infected with her enthusiasm the young associate professor of VSU Ya. A. Ugay, who organized work on the synthesis and research of a new class of semiconductor compounds formed as a result of the chemical interaction of metals of the group (zinc, cadmium) and non-metals of the group (phosphorus, arsenic, antimony) and many other types of compounds. At the same time, co-workers of the Solid State Physics Department used XRD methods to study the state diagrams of zinc-phosphorus, cadmium-phosphorus, zinc-antimony, zinc-arsenic, cadmium-antimony, cadmium-arsenic for the first time, to determine the crystal structures of the numerous compounds formed, and to discover a previously unknown compound Cd_6P_7 [9] (Fig. 4).

But even earlier, aspirant E. P. Domashevskaya used the X-ray spectroscopy method to obtain the world's first experimental evidence of charge transfer from metals of the second and third groups to non-metals of the fifth group during the formation of semiconductor compounds , having measured the shifts of the $K\alpha$-lines of the characteristic X-ray spectrum of metals in these compounds [10]. The results obtained were reported at the All-Union Conference on the Physics and Chemistry of Semiconductors in January 1962 in Leningrad under the chairmanship of Professor N. A. Goryunova, and later at the International Conference on Chemical Bonding in

Fig. 4. K. B. Aleinikova, V. S. Kavetsky, A. V. Arsenov and A. N. Lukin discuss the results of decoding the crystal structure of Cd_6P_7, the first new semiconductor compound they obtained (the Solid State Physics Department, mid-1970s)

Semiconductors in Minsk under the chairmanship of Academician N.N. Sirota, which was attended by such luminaries of semiconductor science as the Americans Goodenough and Muser, the Frenchman Suchet and others. These results were published in Reports of the USSR Academy of Sciences in co-authorship with Ya. A. Ugai, as well as in the materials of international conferences, subsequently translated to the USA.

The fact is that the obtained data on the positive chemical shifts of the $K\alpha$-lines of the metallic elements and the negative chemical shifts on non-metallic elements put an end to the dispute about the mechanisms of formation of chemical bonds in semiconductors and irrefutably substantiated the new donor-acceptor model due to the unshared electron pair of valence electrons in the elements of the Vth group instead of the old speculative sp^3-hybrid model of Muser and Pearson, in which a negative charge should appear on the metallic element.

With these works, the "semiconductor period" begins at the Solid State Physics Department, but without M.A. Levitskaya, who died on March 7, 1963, 3 weeks before her 80th birthday.

In 1967, junior researcher E. P. Domashevskaya defended her candidate's dissertation "X-ray spectroscopy studies of the nature of chemical bonding in semiconductor compounds" (Fig. 5) and continued to study semiconductor compounds with complex atomic composition, combining research with teaching work at the Solid State Physics Department.

After the death of M. A. Levitskaya, her former aspirant, former front-line soldier, Associate Professor Valery Sergeevich Kavetsky, who was also the dean of the Physics Department, which had recently become an independent department, having separated from the mathematicians as part of the Physics and Mathematics Department in 1959, became the head of the Solid State Physics Department.

And then, from the beginning of the 70s, a new method of ultra-soft X-ray spectroscopy was involved in active research of interatomic interaction and electron structure in semiconductors. This was primarily due to the acquisition, on the initiative of E. P. Domashevskaya, of a unique device, an X-ray spectrometer-monochromator, developed at the Leningrad University by A. P. Lukirsky, the son of the famous academician P. A. Lukirsky, a colleague and employee of A. F. Ioffe. This device (the 13th in a row) was built in Leningrad at the

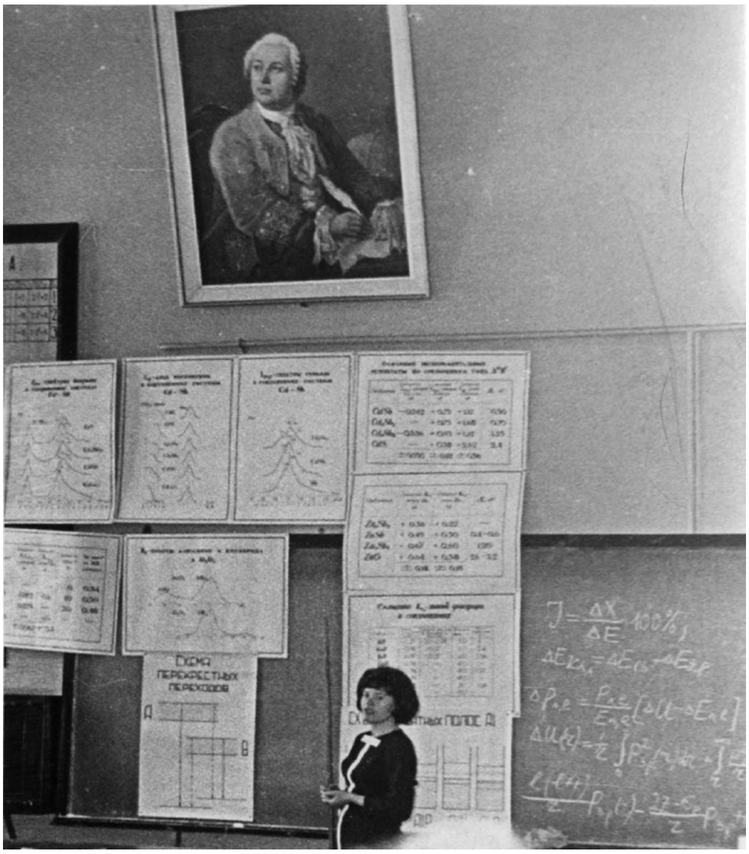

Fig. 5. E. P. Domashevskaya defends her PhD thesis at the Academic Council of the Physics Faculty of Voronezh State University in 1967

experimental plant of the NPO "Burevestnik" under the supervision of its general director N. I. Komyak. In Voronezh, the device was constantly improved in the process of work by assistant V. A. Terekhov (Fig. 6), who transferred it to oil-free means of obtaining a high vacuum, modernized the recording means and achieved the best sensitivity of the device in the USSR.

The features of our experimental approach to determining the nature of interatomic interaction in solids consisted of the complex use of two methods: X-ray spectroscopy (XS) and X-ray electron spectroscopy (XES). This combination of methods creates a unique opportunity to obtain information on the distribution of both the integral density of states of valence electrons responsible for the chemical bond and the local partial density of states contributing to the integral density of states of all valence electrons with different symmetry of states l of atoms of all types α.

Intensity distribution in XS:

$$I\,(E_k) \sim \Sigma p_{\,l,l-1}(E_k)\, n^{\alpha}_{n,l-1}\,(E_k) + p_{\,l,l+1}\,(E_k)\, n^{\alpha}_{n,l+1}\,(E_k), \quad (1)$$

and intensity distribution in XES:

$$I\,(\mathrm{E}_k) \sim \Sigma\Sigma\, c^{a} \sigma^{\alpha}_{n,l}\,(E_k)\, n^{\alpha}_{n,l}\,(E_k - h\nu - \varphi_0), \quad (2)$$

where $n^{\alpha}_{n,l}$ is the local partial density of states of an element of type α with concentration c_{α}; $p_{l,l+1}$ – transition probability factor; $\sigma_{\alpha n,l}$ – weight factor, which has the meaning of photoionization cross-section.

Thus, we performed X-ray spectral studies on a unique laboratory device RSM-500. At the same time, X-ray electron spectra had to be taken in Moscow, mainly in the laboratory of Academician V. I. Nefedov at the Institute of General and Inorganic Chemistry named N. S. Kurnakov of AN USSR or in the laboratory of Professor Yu. A. Teterin at the Kurchatov Institute of Nuclear Physics. The first X-ray electron spectrometers in the USSR from Varian and Hewlett Packard appeared in these centers.

It is precisely thanks to the combination of two methods – X-ray electron spectroscopy and X-ray spectroscopy – on numerous semiconductor binary and ternary compounds of the different types ($A^{III}B^{V}$, $A^{II}B^{VI}$, $A^{I}B^{V}$, $A^{I}B^{VII}$, $A^{II}B^{V}$, $A^{II}B^{IV}C^{V}_2$, $A^{I}B^{III}C^{VI}_2$) were experimentally discovered and theoretically substantiated previously unknown patterns of interaction of *d*-electrons of metals with *s*,*p*-electrons of non-metals elements, which are resonant in nature and are caused by the

Fig. 6. Future professor, assistant V. A. Terekhov obtains the first results on the new ultrasoft X-ray spectrometer-monochromator RSM-500 (1970)

mutual arrangement of the interacting elements, metals and non-metals, in the periodic table [11, 12]. This interaction of a fundamental nature manifests itself regardless of the complexity of the composition and nature of the compound or alloy and consists either in the splitting of the *s*, *p*-band and the expulsion of *s*, *p*-states from the *d*-band at $Ed = Es, p$ (*d-s,p* resonance) [13], or simply in the repulsion of *s*, *p*-states by *d*-electrons at $Ed \neq Es,p$ with the simultaneous appearance of an admixture of *s*, *p*-states in the *d*-band.

For the theoretical description of the phenomenon of d-s,p resonance, E.P. Domashevskaya and her co-workers , O. V. Farberovich and S. I. Kurgansky (Fig. 7), were the first in Russia to implement a modified method of orthogonalized plane waves OPW, which allows calculating the band spectrum of compounds with *d*-metals [14].

Thus, in the 70s, at the Department of Solid State Physics of Voronezh State University, under the supervision of E. P. Domashevskaya formed a unique scientific direction that combines experimental and computational methods for studying the atomic and electronic structure of semiconductor materials and the nature of interatomic interactions in solids and thin films. The result of this most active period of development of experimental and theoretical studies of the atomic and electronic structure of semiconductor compounds of various types was the successful defense of the doctoral dissertation of E. P. Domashevskaya at the Academic Council of the Institute of Metallophysics of the National Academy of Sciences of the Ukrainian SSR in Kyiv in 1979 "The nature of interatomic interaction and

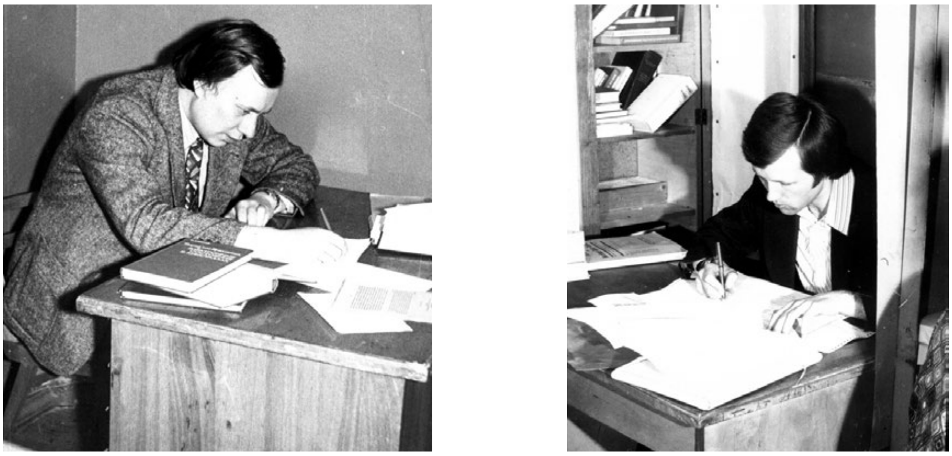

Fig. 7. Research Associates O. V. Farberovich and S. I. Kurgansky develop a software package for calculating the electronic structure of semiconductor compounds using the modified method of theorthogonalized plane waves MOPW (the Solid State Physics Department)

patterns of the structure of the energy spectrum of valence electrons in semiconductors" [15] (Fig. 8). Thus, 16 years after the death of M.A. Levitskaya, a doctor of physical and mathematical sciences appeared at the Solid State Physics Department, and soon after the approval of the doctoral dissertation by the Higher Attestation Commission in 1980, E. P. Domashevskaya became the head of the Solid State Physics Department in the position of professor.

In 1978, the VSU Physics Department celebrated the 95th anniversary of M. A. Levitskaya's birth. The Presidium was represented by all of Maria Afanasyevna's former aspirants, starting with Professor L. P. Rapoport and ending with E. P. Domashevskaya (Fig. 9).

And five years later, in 1983, the Physics Department celebrated the 100th anniversary of M. A. Levitskaya's birth not only with a memorial conference, but also with a major cultural event

Fig. 8. E. P. Domashevskaya defends her doctoral thesis in Kyiv in 1979

in honor of the outstanding female physicist. Professor E. P. Domashevskaya, already in the role of head of the Solid State Physics Department, developed and approved at the Academic Council of the Physics Department a project for the artistic decoration of the back wall of the Large Physics Auditorium named after Professor M. A. Levitskaya in the form of a wall fresco painting, in the center of which Honored Painter of the Russian Federation Utenkov depicted Maria Afanasyevna Levitskaya surrounded by students (Fig. 10 and Fig. 11).

Following the study and discovery of *d-s,p* resonance, Domashevskaya's student O. V. Farberovich, studied in detail and generalized the resonance nature of the *f-s,p* interaction of *f*-electrons of rare-earth metals with *s, p*-electrons of non-metals. In his works, an approach based on the density functional theory was proposed, which allows one to take into account both the band nature of the states of *f*-electrons and their strong localization in a single scheme. Within the framework of such a universal approach, several basic powerful methods for calculating the band structure were implemented, differing in the type of effective potential: the method of orthogonalized plane waves (OPW), the method of augmented plane waves (APW), the Green's function method (GF), the method of linear combination of atomic orbitals (LCAO), the modified OPV method (MOPV), which was interpreted as a combination of the OPV and LCAO methods. As a result of joint work with Professor K. A. Kikoin (I. V. Kurchatov Institute of Atomic Energy), a theory of mixed valence of rare earth compounds was created.

Based on these theoretical studies in the field of multiplet structure, O. V. Farberovich defended his doctoral dissertation in 1985 [16] at the Institute of Steel and Alloys (Moscow) in the department of Nobel Prize laureate A. A. Abrikosov with the support of Nobel Prize laureate V. L. Ginzburg. Thus, in 1985, O. V. Farberovich became the youngest doctor of physical and mathematical sciences at Voronezh State University.

Fig. 9. 95th anniversary of M. A. Levitskaya's birthday. In the presidium from left to right: Professor P. V. Cherpakov, Associate Professor E. P. Domashevskaya, Associate Professor A. N. Latyshev, Associate Professor V. S. Kavetsky (Dean of the Physics Faculty), Associate Professor A. M. Meleshina, Professor L. P. Rapoport and Associate Professor N. A. Ignatiev

Fig. 10. Honored Artist of the Russian Federation Utenkov presents to the staff of the Solid State Physics Department his original fresco on the wall of the Large Physics Auditorium named after Professor M. A. Levitskaya, painted for the 100th anniversary of her birth in 1983.

Further development of research at the SSP department was associated with the emergence and development of a new interdisciplinary science, technology and engineering – microelectronics. In the first half of the last century in Voronezh the giant of the electronics industry was soon created - the scientific and production association NPO "Elektronika" with the active participation of graduates of the Physics Department of VSU. The Departments of Voronezh State University: Electronics (Head of Department, Associate Professor N. V. Kotosonov), Semiconductor Physics (Head of Department, Professor N. G. Nifontov, and later Professor V. F. Synorov), Solid State Physics (Head of Department, Associate Professor V. S. Kavetsky, Associate Professor N. A. Ignatiev, Professor E. P. Domashevskaya), Inorganic chemistry (Head of Department, Professor Ya. A. Ugay) began to cooperate with NPO "Elektronika" and train personnel for this rapidly developing industry in new specialties, including specialty 200.200 – microelectronics and semiconductor devices and 200.300 – semiconductor materials.

New requirements of the time and scientific and technological progress shifted the center of gravity of research from bulk semiconductor crystals and materials to the area of planar technologies – thin films and thin-film metal-semiconductor (MS) and metal-insulator-semiconductor (MIS) heterostructures.

By this time (early 70s) an outstanding result was obtained by V. A. Terekhov with her co-workers V. M. Andreeshchev and V. M. Kashkarov on our RSM-500 device: we discovered in the $L_{2,3}$ spectra

Fig. 11. Successor of M. A. Levitskaya, Professor E. P. Domashevskaya, Head of the Solid State Physics and Nanostructures Department of Voronezh State University (1980–2020) gives a lecture in the Large Physics Auditorium named after Professor M. A. Levitskaya against the background of a wall fresco with her image

of heavily doped silicon single crystals δ-shaped localized maxima in the forbidden zone, caused by the presence of donor impurities of phosphorus, arsenic, antimony with a concentration of about 10^{-4} at. %.

Only ten years later these results were reproduced in the USA, and then only using synchrotron radiation. Since then, we have been developing the physics of localized states, which play a decisive role in the electrophysical and optical properties of heavily doped and disordered semiconductors. The developed approach was successfully used by us in the study of the total local and partial densities of state of atoms in disordered condensed media and amorphous semiconductors and dielectrics. Special attention was paid to the study of localized states in the forbidden zone, providing direct information on the nature and number of defects in real materials: heavily doped, ion-implanted semiconductors, hydrogenated amorphous silicon and heterostructures, developed by our colleagues and co-authors at the A. F. Ioffe Physical-Technical Institute of the USSR Academy of Sciences, the P. N. Lebedev Physical Institute of the USSR, the Nizhny Novgorod State University and other institutes. The successful development of this direction was reflected, first of all, in the content of the doctoral dissertation of Vladimir Andreevich Terekhov "Local density of electron states in disordered semiconductors" (1994) [17].

The methods developed within the framework of these studies were successfully used to analyze thin-film systems, coatings and composites within the framework of cooperation with industrial partners JSC "NIIET", VZPP "Mikron", VZPP "Sborka", JSC "RIF" (Voronezh) and were reflected in the subsequent doctoral dissertations of Yurakov Yu. A. "Electronic structure and physical properties of thin metal-silicon films" (2000) [18], Turishchev S. Yu. "Electronic and energy structure of nanoscale structures based on silicon and its compounds" (2014) [19] and Lenshina A. S. "Formation and functional properties of nanostructures based on porous silicon" (2021) [20].

Nanophysics at the Department of SSPNS

Since 2007, the Department of Solid State Physics of Voronezh State University has been called the Department of Solid State Physics and Nanostructures (SSPNS), already having significant scientific achievements in the field of nanostructure and nanomaterial research.

Nanoelectronics emerged as microelectronics developed, and the SSPNS Department of took part in this process. The transition to very large integrated circuits (VLSI) and the gigantic density of active elements packing per unit area of the substrate crystal rapidly dictated new requirements for the ultra-small sizes of these circuit elements. In the course of developing new technologies, there was a gradual transition from micron scaling (10^{-6} m) to the nanometer range (10^{-9} m) of manufacturing active elements of microcircuits and the development of new nanotechnologies. In new artificial materials – superlattices, quantum wires and quantum dots – new "quantized" physical properties were discovered – the quantum Hall effect, quantum electrical conductivity, etc. The SSP Department did not have to radically restructure itself, because we have always used nanophysics methods: diffraction and interference of electrons and quanta on the atomic planes of the crystal, located at subnanometer, angstrom distances (1 Å = 0.1 nm). But the most important thing is that the depth of the informative layer in our unique method of ultra-soft X-ray spectroscopy, limited by the depth of the X-ray characteristic radiation output of a long wavelength of ~10 nm, is also ~10–100 nm.

However, it should be noted that experimentally we obtain averaged information from the entire nanolayer, which has a thickness of several tens of unit cells. But theoretically, it was possible to dismember even one unit cell into separate layers and study the features of the main properties of such a model object in comparison with a real material. This approach was implemented in the works of Sergey Ivanovich Kurgansky, who, in the conceptual approximation of the local density functional within the framework of the computational scheme of the film method of linearized augmented plane waves (LAPW), created a unified method for calculating the electronic band structure, X-ray emission and photoelectron spectra of thin films of subnanometer thickness. He showed that the structure of the valence band in metal oxide films of high-temperature superconductors of the $YBa_2Cu_3O_{7-X}$ type is determined by the interaction of copper d-electrons with oxygen p-electrons, which is well described by the *d*-*s*,*p*-resonance model. At the same time, due to the peculiarities of the crystalline structure of the unit cell of these compounds and the isolation of its cuprate layers from each other by Ba–O layers, this model works separately in each cuprate layer with the stoichiometry of CuO and CuO_2. S. I. Kurgansky defended his doctoral dissertation "Electronic structure of thin films of complex metal oxides" in 1996 [21].

Subsequently, the range of methods and studied nanosystems expanded. The method of augmented cylindrical waves (ACW) was used to study the electronic structure of one-dimensional nanosystems – single-wall carbon and silicon nanotubes. Then, a study was conducted of the atomic and electronic structure of a number of zero-dimensional nanosystems - metal-silicon and metal-germanium clusters containing one atom of a transition metal (Sc, Ti, V, Cr, Y, Zr, Nb, Mo) and up to twenty atoms of silicon or germanium [22]. Experimentally, the electronic structure of these clusters was much later studied using photoelectron spectroscopy. A comparison of the calculated densities of states with the experimental photoelectron spectra showed that the shape of the density of states of the main isomer with the highest binding energy is close to the experimental spectrum.

Also among the first steps towards theoretical study of zero-dimensional nanosystems was the study of small metal particles (SMP) with sizes of several hundred nanometers. To study the spectral characteristics of SMP, Professor O. V. Farberovich and aspirant Larisa Kurkina developed a time-dependent density functional method at the SSP Department, on the basis of which a series of unique works were carried out to study the nature of optical spectra in SMP. L. I. Kurkina successfully defended first her candidate's and then her doctoral dissertation "Electronic properties of *s*,*p*- and 3*d*-metal clusters" in 1997 [23], becoming at the age of 31 the youngest doctor of physical-mathematical sciences at the Physics Faculty.

Also, within the framework of the local spin density functional method, but using the "atom in jelly" model, calculations were carried out for Al and Fe clusters of various sizes containing up to 130 atoms, which revealed a non-monotonic change in the electronic structure with an increase in the cluster size and a non-monotonic size dependence of the ionization potential and magnetic moment. It was shown that in aggregates containing up to several tens and even hundreds of atoms, quantum-size effects are clearly manifested, which mainly determine the unique properties of clusters.

In 1999, at an extended meeting of the Academic Council and the Scientific and Technical Council of VSU, the SCIENTIFIC SCHOOL of Evelina Pavlovna Domashevskaya in the field of electronic structure of solids [24] was approved among 11 leading scientific schools of VSU with the presentation of a CERTIFICATE (Fig. 12) and a MEMORIAL MEDAL of VSU.

In the experimental part of the work, the development of nanophysics and nanotechnology continued with the development of manufacturing technology and the study of the electron structure, optical and electrical properties of porous silicon (*por*-Si), which are fundamentally different from the properties of single-crystal silicon, since por-Si is a typical nanomaterial. First of all, it luminesces


СВИДЕТЕЛЬСТВО

Решением Ученого Совета и Научно-технического Совета ВГУ
среди ведущих научных школ университета
утверждена научная школа профессора
ДОМАШЕВСКОЙ ЭВЕЛИНЫ ПАВЛОВНЫ
в области электронного строения твердого тела
с вручением руководителю школы
ПАМЯТНОЙ МЕДАЛИ
ВОРОНЕЖСКОГО ГОСУДАРСТВЕННОГО УНИВЕРСИТЕТА.

Председатель Ученого Совета университета,
ректор, профессор И.И. Борисов
Председатель Научно-технического Совета,
проректор по научной работе, профессор А.С. Сидоркин
28.04.99 г.

Fig. 12. Certificate of approval by the Academic Council and the Scientific and Technical Council of VSU of the SCIENTIFIC SCHOOL of E. P. Domashevskaya with the presentation of the MEMORIAL MEDAL of VSU

perfectly in the visible region, changing the colors of luminescence from red to green-blue, depending on the size of the pores and, consequently, on the size of the *por*-Si nanocrystals coated with nanolayers of oxide and amorphous phases. To determine the complex phase composition of this nanomaterial using ultra-soft X-ray spectroscopy methods, an algorithm was developed and a special computer program was created to determine the component composition of complex multiphase systems including amorphous phases [25]. A significant part of these developments formed the basis of the candidate's and then doctoral dissertations of A. S. Lenshina. (2021) "Formation and functional properties of nanostructures based on porous silicon" [20].

The transition to the use of low-dimensional systems in microelectronics and condensed matter physics has entailed the intensive development of composite nanomaterial technologies, among which granular metal-dielectric composites with metal particle sizes of about 10-100 nm and possessing unique nonlinear electrical and magnetic properties are of particular interest.

The development of nanocomposite science and technology has led to large-scale studies of ferromagnetic-diamagnetic materials due to the discovery of tunnel magnetoresistance (TMR) in them, an analogue of giant magnetoresistance (GMR), differing in the mechanisms of charge carrier and spin transport. A large number of studies on GMR were published after the discovery of this effect in 1988 by Albert Fert and Peter Grünberg and the awarding of the Nobel Prize to the authors in 2007. As a result, technologies of magnetically hard and magnetically soft materials for microwave electronics, radio electronics, magnetic sensors, bank cards, etc. were developed.

Around this time, our colleagues from the Voronezh State Technical University developed original magnetron technologies for producing film nanocomposites of metal-dielectric and metal-semiconductor of various variable compositions and studied their electromagnetic properties. The results of these studies were summarized in the collective monograph "Nonlinear Phenomena in Nano and Microheterogeneous Systems" by S. A. Gridnev, Yu. E. Kalinin, A. V. Sitnikov, O. V. Stognei, published in 2012 [26].

At the same time, at the SSPNS Department of Voronezh State University, under the supervision of Head Professor E. P. Domashevskaya, they began to study the influence of the atomic composition, atomic structure and concentraition of different components on nonlinear electromagnetic properties using samples synthesized at VSTU. The results of these studies were summarized in the candidate dissertations of aspirants S. A. Storozhilov "Atomic and electronic structure of metal-insulator nanocomposites $(Co_{41}Fe_{39}B_{20})_x(SiO_2)_{1-x}$ and $(Co_{45}Fe_{45}Zr_{10})_x(SiO_2)_{1-x}$" (2008), Builov N. S. "Atomic and electronic structure of multilayer nanostructures with metal-composite layers and non-magnetic interlayers" (2020), Ivkov S. A. "Features of structural and transport properties of nanocomposites $Co_x(MgF_2)_{100-x}$ and $(Co_{45}Fe_{45}Zr_{10})_x(MgF_2)_{100-x}$" (2022) and Peshkov Ya. A. "Phase composition, electronic structure and electric transport properties of multilayer nanostructures based on CoFeB and CoFeZr" (2024). Thus, starting from the late 1970s and up to the present time, 15 doctors of physical and mathematical sciences and more than 60 candidates of sciences have been trained in the scientific school of solid state physics and nanostructures (Fig. 13).

In 2012, Evelina Pavlovna Domashevskaya was awarded the Certificate of the Prime Minister of the Russian Federation Vladimir Vladimirovich Putin *"For the support provided in the elections of the President of the Russian Federation in March 2012, a huge contribution to the development of nanotechnology and solid state physics in the territory*

Fig. 13. Doctors of Physical and Mathematical Sciences in the Scientific School of Solid State Physics and Nanostructures of VSU

of the Russian Federation and in connection with the celebration of her birthday."

Synchrotron studies of nanomaterials

The history of synchrotron studies in VSU is associated with the cooperation of the Solid State Physics Department with German scientists from the University of Leipzig (GDR) in the second half of the 20th century. The first work of junior research fellow E. P. Domashevskaya (co-authored with Ya. A. Ugay) was published in 1965 in the Proceedings of the University of Leipzig based on the results of correspondence participation in the work of the 1st International Conference on X-ray Spectroscopy in 1964, chaired by Professor Armin Meisel.

Twenty years later, in 1984, Professor E. P. Domashevskaya, already the head of the Department of Physics and Solids, took part in the Jubilee International Conference (20 years) on X-ray and Intrashell Processes in Atoms, Molecules and Solids, which was organized by the same Professor of the University of Leipzig Armin Meisel and co-chaired by Nobel laureate Kai Siegbahn, the creator and developer of X-ray electron spectroscopy at the oldest university in Europe, Uppsala (Sweden). Many outstanding scientists from different countries took part in the work of this conference, among which one of the largest delegations was represented by scientists from Sweden. From the USSR, world-famous scientists in the field of X-ray and electron spectroscopy took part, professors Igor Borisovich Borovsky (Moscow), Mikhail Arnoldovich Blokhin (Rostov-on-Don), academician of the Academy of Sciences of the Ukrainian SSR Vladimir Vladimirovich Nemoshkalenko (Kyiv), professors Vadim Ivanovich Nefedov (Moscow), Tatyana Mikhailovna Zimkina (Leningrad), Miron Yankelevich Amusya (Leningrad), Viktor Aleksandrovich Trapeznikov (Izhevsk), Igor Yakovlevich Nikiforov (Rostov-on-Don), Vladimir Filippovich Demekhin (Rostov-on-Don), Evelina Pavlovna Domashevskaya (Voronezh), Ernst Zagidovich Kumaev (Rostov-on-Don). Sverdlovsk), Lev Nikolaevich Mazalov (Novosibirsk), Mart Elango (Tartu). At this conference E.P. Domashevskaya made the report in English entitled "d-s,p and f-p resonanses in compounds" [27]. She then participated in similar conferences in Berkeley (USA) in 1990, in Rome (Italy) in 1996, in Tokyo (Japan) in 1998, in Uppsala (Sweden) in 2003 (Fig. 14), in Berlin (Germany) in 2007.

In 1996, on the initiative of E. P. Domashevskaya, the 1st Russian-German seminar dedicated to the 100th anniversary of Roentgen's discovery of X-ray. The next 2-nd X-ray Seminar was held in Berlin in 1997, and the third one in Yekaterinburg in 1999. And in November 2001, as a result of close cooperation with German colleagues and, in many

Fig. 14. E. P. Domashevskaya among the participants of the 9th International Conference on Electron Spectroscopy in the Nobel Hall of the oldest university in Uppsala (Sweden, 2003)

ways, thanks to the scientific and organizational efforts of two world-famous female physicists from St. Petersburg University, professors Tatyana Mikhailovna Zimkina and Vera Konstantinovna Adamchuk, a Russian-German channel and a Joint Use Laboratory were opened in Berlin at the new latest generation synchrotron BESSY II (Fig. 15), the research program of which included the first project from VSU in 2002, "Study of the features of the electronic structure and the nature of photoluminescence in porous materials and materials containing quantum dots, direct and indirect semiconductors (Si, GaP, InP, GaAs)".

Since then, several dozen projects have been carried out to study nanomaterials, nanostructures and nanocomposites with various functional

Fig. 15. Opening of the Russian-German Channel and the Joint Laboratory at the Berlin Synchrotron BESSY II in November 2001

properties: luminescent, gas-sensitive and magnetic, using the BESSY II synchrotron radiation, the results of which are reported at various international conferences. And Ruslan Ovsyannikov, a former graduate student of Professor E. P. Domashevskaya (Voronezh State University) and a postgraduate student of Professor Eberhardt (Technical University of Berlin) is currently working as a leading researcher at the Berlin synchrotron BESSY II.

Using SR, unusual effects of the interaction of complex silicon-based nanosystems with electromagnetic radiation of nanometer wavelengths (ultrasoft X-ray synchrotron radiation) were discovered for the first time as a result of interference and diffraction of incident and reflected radiation from silicon nanocrystals or interfaces of multilayer structures. We called this new effect the "intensity reversal effect". Such effects appear at the absorption edges of silicon obtained by synchrotron radiation with a wavelength commensurate with the size of nanocrystals or the thickness of nanolayers. Then, pre-edge interference of synchrotron radiation from nanolayers of "stretched" silicon of a certain thickness was discovered in "silicon on insulator" structures. All these newly discovered effects formed the basis of the doctoral dissertation (2014) of a young scientist, now the head of the Department of General Physics at the Physics Faculty of Voronezh State University, Sergei Yuryevich Turishchev [19], who leads a group of Voronezh synchrotron scientists, which includes master's students, postgraduate students and young employees of the Physics Faculty (Fig. 16).

Nanosized monocrystals of oxide materials

Systems and devices created on the basis of nanomaterials are increasingly used in various fields of modern engineering and technology. The characteristics of such systems are fundamentally different from those of their analogues created using traditional technologies. One example of such materials are oxide nanowires. The unique physical properties of nanowires are determined by several factors: the nanoscale of crystallites; a single-crystal structure with a low degree of defectiveness; and extremely pronounced anisotropy of nanocrystals.

Since the 2000s, a new direction related to the physicochemical studies of filiform nanomaterials has been developing at the SSPNS Department in the group of Senior Researcher S. V. Ryabtsev. Using the gas transport method, filiform nanocrystals of oxide wide-bandgap semiconductors SnO_2, ZnO, In_2O_3 and some others were synthesized and studied [28]. By changing the parameters of gas transport synthesis, it is possible to obtain various nanocrystalline forms of oxide materials (Fig. 17). The resulting nanomaterials exhibit the highest sensitivity to the adsorption of a number of gases. High-quality

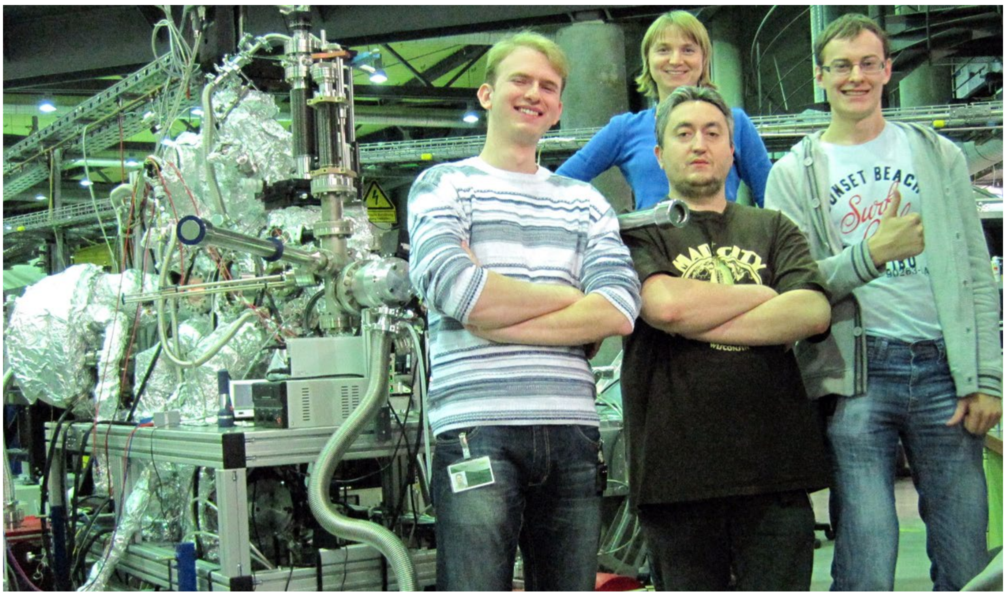

Fig. 16. A group of young scientists of the Solid State Physics Department headed by S. Yu. Turishchev at the Russian-German Channel BESSY II synchrotron in Berlin in 2014: (from left to right) Dmitry Nesterov, Sergey Turishchev, Dmitry Spirin and Olga Chuvenkova

semiconductor gas sensors were developed on their basis [29]. Combining several sensors (receptors) with different selectivity into a common device with appropriate data processing made it possible to create a laboratory model of the device, the so-called "electronic nose", which, in a certain sense, is an analogue of the human olfactory organ. The result of the intensive development of nanotechnology was the successful defense of several candidate's dissertations, and then a doctoral dissertation by S. V. Ryabtsev "Electrical and optical properties of various nanoforms of tin oxide" in 2011 [30].

Nanoheterostructures based on AIII BV and the Joint Laboratory with the A. F. Ioffe Physico-Technical Institute of the Russian Academy of Sciences

Quantum-size AIIIBV heterostructures invariably attract serious attention from researchers and technologists. All of the AIIIBV-based nanoheterostructures that we study are formed at the Physico-Technical Institute named A. F. Ioffe of RAS by a group of co-workers of Nobel Prize laureate Zhores Ivanovich Alferov, with whom the Solid State Physics Department has had long-standing close scientific contacts [31]. The formation of self-organizing low-dimensional semiconductor layers on AIII BV single crystals turned out to be especially promising due to the possibility of obtaining spatial (3D) confinement of electrons in stable (dislocation-free) clusters, conductivity and high radiation efficiency due to the low density of defects. Using synchrotron radiation SR, we obtained for the first time the spectra of the near fine structure of X-ray absorption in the region of the main absorption edge of phosphorus $PL_{2,3}$, reflecting the local density of states in the conduction band in nanostructures with InP quantum dots grown on GaAs <100> by the method of gas-phase epitaxy from metal-organic compounds, and in porous InP layers obtained by anodic pulsed electrochemical etching of InP <100> single-crystal wafers [32].

In 2008, at the International Conference on Heterostructures dedicated to the 90th anniversary of the A. F. Ioffe Physico-Technical Institute of the Russian Academy of Sciences, chaired by Academician Zh. I. Alferov, professor Domashevskaya E. P. made the plenary report on the results of joint research of VSU and PTI

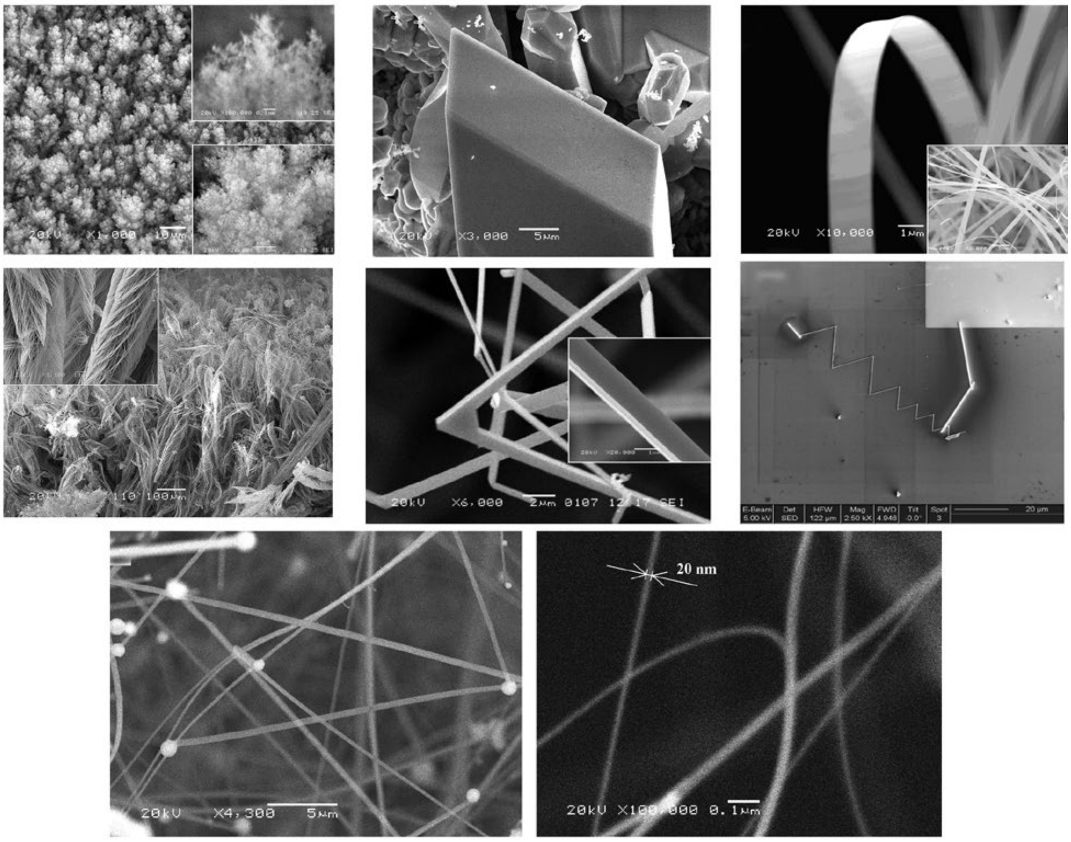

Fig. 17. Various shapes of SnO_2 nanocrystals obtained by gas transport synthesis

the "Diagnostics of nanoheterostructures using XANES and XRD" (Fig. 18).

Simultaneously with these studies, a group of postgraduate students headed by P. V. Seredin, working on the problem of matching the parameters of crystal lattices in semiconductor heterostructures, showed that as a result of the decomposition of epitaxial solid solutions of three-component ($Al_xGa_{1-x}As$, $Ga_xIn_{1-x}P$, $In_xGa_{1-x}As$), four-component ($Ga_xIn_{1-x}As_yP_{1-y}$), and even five-component $Al_xGa_yIn_{1-x-y}As_zP_{1-z}$ [33], nanostructures can spontaneously arise, representing superstructural phases of ordering with the formation of a domain structure. In 2012, P. V. Seredin defended his doctoral dissertation "Substructure and optical properties of epitaxial heterostructures based on A3B5" [34]), and at the age of 32 became the youngest doctor of physical and mathematical sciences in the history of the Physics Department of Voronezh State University. The results of P. V. Seredin's doctoral dissertation formed the basis of his monograph "New physical phenomena in heterostructures based on A^3B^5 semiconductors. Promising approaches to creating optoelectronics of the future", published in Moscow in 2015 [35]. The book describes a new physical phenomenon in semiconductor heterostructures - the spontaneous emergence of periodically ordered structures on the surface and in epitaxial films of A3B5 semiconductors. The regularities of the phenomenon of the emergence of superstructural ordering phases are described, which makes it possible to obtain inclusions of narrow-band semiconductors in a

Fig. 18. International Conference on Heterostructures at the A. F. Ioffe Physico-Technical Institute of the Russian Academy of Sciences chaired by Academician Zh. I. Alferov

wide-band matrix, thereby creating the basis for a new technology for obtaining ordered arrays of inhomogeneities - the basis for a new generation of opto- and microelectronics.

In 2014, the Joint Laboratory of Physics of Nanoheterostructures and Semiconductor Materials (VSU-Ioffe Physical-Technical Institute of the Russian Academy of Sciences) was officially established in the form of a Consortium between the Federal State Budgetary Educational Institution of Higher Education “Voronezh State University” and the Federal State Budgetary Institution of Science “Ioffe Physical-Technical Institute of the Russian Academy of Sciences”. The participants of the Consortium are the Solid State Physics and Nanostructures Department of Voronezh State University and the Laboratory of Semiconductor Luminescence and Injection Emitters of the Ioffe Physical-Technical Institute. The heads of the Joint Laboratory on the part of Voronezh State University were young Doctor of Sciences Pavel Vladimirovich Seredin, and on the part of the Ioffe Physical-Technical Institute - former graduate of VSU Solid State Physics Department, now leading researcher, Doctor of Sciences, Laureate of the All-Union Lenin Komsomol Prize Ivan Nikitich Arsentyev.

Research areas developed in the Joint Laboratory of Voronezh State University and the Ioffe Physical-Technical Institute:

– fundamental research into the features of the atomic and electronic structure, optical and electrophysical properties of semiconductor heterostructures based on A3B5;

– modeling of physical processes in semiconductor technology;

– diagnostics of low-dimensional and quantum-dimensional systems by diffractometric and spectroscopic methods;

– development of fundamental principles for the creation of new bioactive materials that match the composition, morphological and physicochemical properties of human dental and bone tissue;

– studies of metabolic processes in the hard tissues of the human tooth;

Some of the projects implemented in the Joint Laboratory:

1. Project No. 3.130.2014/K, on the topic: “Development of physical and technological approaches to the formation and diagnostics of epitaxial integrated AIIIBV/Si heterostructures” carried out within the framework of the Project part of the state assignment to universities of the Russian Federation 2014-2016 (Head P.V. Seredin) (2014-2016).

2. Grant of the Russian Foundation for Basic Research 16-32-50003 mol_nr “Research into the main capabilities of controlled self-organization, self-assembly and superstructuring in epitaxial solid solutions of A3B5 semiconductors and their integration with silicon technology” (Head P.V. Seredin) (2016) .

Fig. 19. Head of SSPhNS Department, Professor E. P. Domashevskaya and Associate Professor P. V. Seredin at the Joint Laboratory of VSU–PhTI RAS in 2019 (VSU, University Square, 1)

3. Grant of the President of the Russian Federation MD-188.2017.2 for state support of scientific research of young Russian scientists-doctors of science “Epitaxial heterostructures A3B5/por-Si with high functional properties: development of production technology and fundamental research” (Head P.V. Seredin) (2017-2018).

4. RSF Grant 19-72-10007 “Study of the formation features of hybrid semiconductor nanoheterostructures of reduced dimensionality on porous silicon” (Head A.S. Lenshin) (2019-2021).

5. RSF Grant 16-15-00003-P “Development of effective methods of preventive dental care by normalizing metabolic processes in hard tissues of the human tooth in vivo using biomimetic materials with high remineralization potential” - extension (Head P.V. Seredin) (2019-2020).

6. RSF Grant 17-75-10046 “Development of the basics of precision diagnostics of dental caries of different levels of formation based on fundamental research of biogenic samples and biomimetic model environments” (Head D.L. Goloshchapov) (2017-2019).

7. RSF Grant 25-22-00292 “Features of the structure, sorption and luminescent properties of a hybrid core-shell system based on porous silicon for targeted drug delivery” (Head E.P. Domashevskaya) (2025).

In 2020, Honored Scientist, Professor Evelina Pavlovna Domashevskaya handed over the post of head of the Solid State Physics and Nanostructures Department to Doctor of Physical and Mathematical Sciences, Associate Professor Pavel Vladimirovich Seredin, Laureate of several Grants of the President and the Russian Science Foundation.

Thus, numerous directions of the scientific school of SOLID STATE PHYSICS AND NANOSTRUCTURES in Voronezh State University, known far beyond Russia, continue and develop, the foundations of which were laid 90 years ago by an outstanding female physicist, Professor Maria Afanasyevna Levitskaya, who headed the Solid State Physics Department in Voronezh State University for more than 25 years, and were continued by Professor Evelina Pavlovna Domashevskaya, who headed the same Department in Voronezh State University for about 40 years.

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