Graphene in Russia: The Main Centers, Research Areas, Results

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Abstract

Russian graphene research centers are presented, in which the most significant results were obtained. The cities, scientific groups, their leaders, main research areas are listed: methods of synthesis and diagnostics of graphene and graphene-like structures, theoretical methods in the application to graphene materials, devices based on graphene and related structures - sensors of physical characteristics, fuel cells, biosensors etc., the application of graphene and related 2D materials in electronics, photonics, spintronics, optoelectronics, bioelectronics. The large-scale production of graphene and graphene-like structures is also covered. The main sources of publications of Russian researches and their colleagues are also listed. Copyright © VBRI Press.

Keywords: Research centers, grapheme, graphene-like structures, sensors.

Introduction

In Russia, the study of graphene is one of the priority research areas. Research is conducted in a number of leading institutes of the Russian Academy of Sciences (RAS), universities and scientific research institutes. Russian studies of graphene are characterized by a wide variety of approaches. Currently, many potential applications of graphene are being discussed for the creation of electronic and electro-optical devices, sensors, advanced materials, etc. However, the possibility of one or another application of graphene depends on the technology of its production. At present, there are many methods that allow creating both nanometer-sized structures and rather large graphene sheets (up to 75 cm), but there is no mass production. The samples obtained in such approaches are inherently polycrystalline and not always sufficiently free of impurities, which significantly limits the possibility of their application in practice. A lot of research is being carried out to improve the characteristics of such samples, and to optimize their use.

Regular conferences and symposiums on graphene are organized in Russia. The first such conference "Graphene - a molecule and 2D crystal" was held in Novosibirsk in September 1915 [**1**], being the natural result of the work of the monthly Moscow (and then Russian) seminar under the same name, that were held since 2013 in the SPA "Almaz" [Diamond] under the direction of the Dr. Sci. Chem., prof. Gubin S.P., Header of Laboratory of Chemistry of Nanomaterials of Kurnakov Institute of General and Inorganic Chemistry of the RAS. Currently, a several conferences are held annually in Russia devoted to a graphene and individual problems related to its research and use.

Main centers, research areas and results

Studies of graphene properties and other monoatomic nanostructures are being conducted in Russia at present in more than 30 centers.

In **Institute of Microelectronics Technology and High-Purity Materials of the Russian Academy of Sciences (IMT RAS)** (http://www.ipmt-hpm.ac.ru), Chernogolovka, Moscow region (**Fig. 1a**) (the last Russian workplace of A. Geim and K. Novoselov) graphene and a hybrid material of graphene-carbon nanotubes are obtained by the method of chemical vapor deposition (CVD) with a single acetylene inlet at low pressure. A method for direct CVD synthesis of 1-3-layer graphene on the surface of piezoelectric crystals is also developed, the unit cell of which agrees with the graphene lattice (**Fig. 1c**). Both methods make it possible to produce nanocarbon material of high quality. The research is conducted in the groups of Sergey V. Morozov (**Fig. 1b**), Dr. Sc. Phys. & Math, Head of the Laboratory of Physics of Semiconductor Nanostructures, and Arkady N. Redkin, Dr. Sc. Phys. &

Math, laboratory of high-quality and perfect films of IMT RAS. Publications in journals Science, Nat. Phys., Nat. Commun., Physical Review Letters etc.

Fig. 1. (a) IMT; (b) Sergey V. Morozov; (c) Graphene on a substrate of oxidized silicon coated with a nickel film catalyst.

The **Mokerov Institute of Ultra High Frequency Semiconductor Electronics of RAS** (IUHFSE RAS), (http://www.isvch.ru), Moscow, has developed a terahertz laser based on graphene heterostructures (**Fig. 2b**) with electric (injection) pumping, the width of its forbidden band is absent or very small. Used in terahertz electronics and photonics. The research is led by Dr. Sc. Phys & Math, Corr. Memb. of RAS Viktor I. Ryzhy (**Fig. 2a**). Publications in Journals: Phys. Rev. B, J. Appl. Phys., JETP Lett., etc.

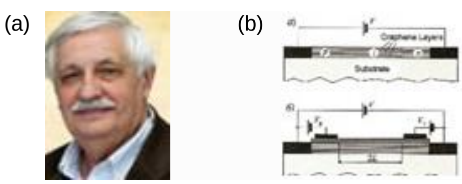

Fig. 2. (a) Viktor I. Ryzhy, (b) Terahertz laser based on graphene heterostructures.

In the **Rzhanov Institute of Semiconductor Physics of the Siberian Branch of RAS (SB RAS)**, (http://www.isp.nsc.ru), Novosibirsk (**Fig. 3a**), optimizes the CVD synthesis of graphene on copper substrates, develops coatings absorbing in the terahertz and infrared ranges, as well as 2D printing technologies for creating memory elements (**Fig. 3c**), vertical heterostructures based on graphene, two-dimensional materials for radiation-resistant electronics, graphene high-frequency transistors and others. The research is led by Dr. Sc. Phys & Math, Prof. Viktor Ya. Prints (**Fig. 3b**), Head of Laboratory of physics and technology of three-dimensional nanostructures, as well as Dr. Sc. Phys & Math Irina V. Antonova. Publications in Journals: Semicond. Sci. Technol., J. Appl. Mech. Tech. Phys., etc.

Fig. 3. (a) ISP SB RAS, (b) Viktor Ya. Prints, (c) 2D printed technologies for creating memory elements.

At the **National Research University of Electronic Technology** (MIET), (https://www.miet.ru), Moscow, Zelenograd (**Fig. 4a**), technology for the maskless modification of graphene was developed - laser oxidative etching below the graphene ablation (**Fig. 4c**) threshold using intense optical radiation (femtosecond laser or UV radiation) for the production of graphene transistor and on its basis a single-crystal matrix receiver of optical, infrared and terahertz radiation [**2**]. The project manager is Dr. Sc. Eng Ivan I. Bobrynetsky (**Fig. 4b**). Publications in Journals: J. Phys. D: Appl. Phys., J. Appl. Crystallogr., J. Semicond., Carbon etc.

Fig. 4. a) MIET; b) Ivan I. Bobrinetsky; c) Characterization of single-layered graphene after laser patterning at a fluence below the ablation threshold for low pulses to overlap. Pseudo-optical image (a). Raman mapping of the same area for G band (b), D band (c) and ID/IG intensity ratio map (d). White dotted lines contour estimated boundaries of the laser processed lines. Black dashed line contour estimated visible wrinkles in graphene responsible for overall nonuniformity of Raman map. Scale-bar is 5 μm.

In the **Vorozhtsov Novosibirsk Institute of Organic Chemistry of SB RAS,** (http://web.nioch.nsc.ru) Novosibirsk (**Fig. 5a**), graphene magnetics (**Fig. 5c**) are developed by successively assembling graphene-like structures carrying alkyl or polyfluoroalkyl groups and stable organic paramagnetic groups [**3, 4**]. The project manager is Dr. Sc. Chem. Evgeny V. Tretyakov (**Fig. 5b**), Head of Lab. of Functional Organic and Hybrid Materials. Publications in Journals: J. Org. Chem., Polyhedron, etc.

Fig. 5. (a) NIOCH; (b) Evgeny V. Tretyakov; (c) Graphene magnetic.

The **Institute of Problems of Chemical Physics of RAS (IPCP RAS)**, (http://www.icp.ac.ru/ru), Chernogolovka, Moscow Region (**Fig. 6a**), created a new object of nanophotonics - nanoclusters of colloidal quantum dots (**Fig. 6c**) and the devices photoelectric conversion of light based on them, as well as graphene ink for printing and the aerogels as electrode material for accumulators and supercapacitors. The project manager is Dr. Sc. Phys. & Math Vladimir F. Razumov (**Fig. 6b**), Member of Corr. RAS, head of lab of photonics of nanoscale structures. Publications in Journals: J. Nanopart. Res., Colloid Polym. Sci., Sol. Energy Mater. Sol. Cells, J. Colloid Interface Sci., Adv. Mater. Lett., Chem. Commun. (London), Usp. Obl. Fiz.-Khim. Polim., High Energy Chem., Colloid J., and others.

Fig. 6. (a) IPCP RAS; (b) Vladimir F. Razumov; (c) Nanoclusters of colloidal quantum dots.

Semenov Institute of Chemical Physics of RAS, (http://chph.ras.ru), Moscow (**Fig. 7a**), specializes in the development of therapeutic agents based on polygraphenes, as well as active materials of electrochemical energy stores based on graphene aerogels. Project manager Ph.D. Valery P. Melnikov (**Fig. 7b**), head of lab of functional polymer systems and composites. Publications in Journals: J. Mater. Chem. A, Chem. Commun. (London), Chem. Eng. J. (Amsterdam, Neth.), Biofabrication, Chem. Phys., etc.

Fig. 7. (a) ICHPH RAS; (b) Valery P. Melnikov.

The **Institute of Applied Physics of RAS** (http://www.iapras.ru), Nizhny Novgorod (**Fig. 8a**), conducts experimental and theoretical studies of the optical properties of graphene, including those under the influence of high-power terahertz radiation (**Fig. 8c**), as well as experiments with single monolayers [**5**]. The project manager is Dr. Sc. Phys. & Math Mikhail D. Tokman (**Fig. 8b**), the Head of Division of Nonlinear Electrodynamics. Publications in Journals: Phys. Rev B, J. Opt. (Kolkata, India), J. Exp. Theor. Phys., Quantum Electron., etc.

Fig. 8. (a) IAP RAS; (b) Mikhail D. Tokman; (c) Optical emission of graphene in the TGT field.

The **Institute of Solid State Chemistry, Urals Branch of RAS,** (http://www.ihim.uran.ru), Yekaterinburg (**Fig. 9a**), conducts studies of regularities in the formation and growth of 3D-, 2D-carbon phases: graphene, multi-layer oxidized graphenes, carbon nanobulbs and multilayered carbon nanotubes (**Fig. 9c**). The project manager is Dr. Sc. Chem. Viktor L. Kozhevnikov (**Fig. 9b**), acad. RAS. Publications in Journals: J. Solid State Chem., Chem. Mater., J. Mater. Chem., etc.

Fig. 9. (a) ISSC UB RAS; (b) Viktor L. Kozhevnikov; (c) Aluminum-Graphene Composite.

Institute of High-Temperature Electrochemistry of the Ural Branch of RAS (IHTE UB RAS), (http://www.ihte.uran.ru), Yekaterinburg (**Fig. 10a**), together with **Zababakhin Russian Scientific Research Institute of Technical Physics** (RFNC-VNIITF), Snezhinsk, (http://www.vniitf.ru) is working on the influence of graphene on the structural and physicomechanical properties of metal matrix composites (**Fig. 10c**) in which metal - aluminum, magnesium, silumin, etc. composites with graphene flakes from 100 nm to 100 µm **[6]**. The project manager is Dr.Sc.Chem. Lyudmila A. Yolshina (**Fig. 10b**), Head of the Laboratory of Chemical Current Sources of the IHTE. Publications in Journals: J. Alloys Compd., Synth. Met., Diamond Relat. Mater., J. Power Sources, etc.

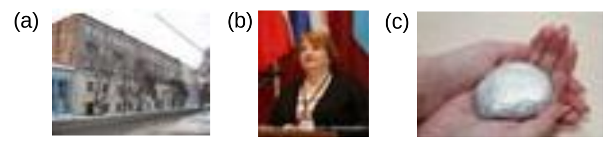

Fig. 10. (a) IHTE UB RAS; (b) Lyudmila A. Yolshina; (c) Aluminum-Graphene Composite.

At the **Institute of Solid State Chemistry and Mechanochemistry of SB RAS**, (http://www.solid.nsc.ru), Novosibirsk (**Fig. 11a**), together with the **Novosibirsk State Technical University** (http://www.nstu.ru) (Chair of Chemistry and Chemical Technology), they have developed several methods of the carbon materials synthesis based on graphene and have investigated their characteristics for use as electrode materials (**Fig. 11c**) for supercapacitors [**7, 8**]. The project manager is Dr. Sc. Chem. Nikolay F. Uvarov (**Fig. 11b**), head of the lab of nonequilibrium solid-phase systems. Publications in Journals: J. Alloys Compd., Thermochim. Acta, J. Appl. Chem. (London, U.K.), etc.

Fig. 11. (a) ISSC SB RAS; (b) Nikolay F. Uvarov; (c) Graphene material for electrodes.

Nikolaev Institute of Inorganic Chemistry (NIIC) of SB RAS, (http://www.niic.nsc.ru), Novosibirsk (**Fig. 12a**), explores the possibilities of using graphene and its compounds in the elements and systems of the AMSE (armament, military and special equipment) [**9**], develops graphene nanocomposites (graphene memristors, **Fig. 12c**) to create memory elements of a new generation of electronics [**10**]. The project manager is Dr. Sc. Phys & Math Alexander V. Okotrub (**Fig. 12b**), head of lab of the physical chemistry of nanomaterials. Publications in Journals: ACS Nano, Carbon, Beilstein J. Nanotechnol., and etc.

Fig. 12. (a) NIIC SB RAS; (b) Alexander V. Okotrub; (c) Graphene memristor.

In the **Kotelnikov Institute of Radioengineering and Electronics of RAS**, (http://www.cplire.ru), Moscow (**Fig. 13a**), highly porous radio-absorbing materials (**Fig. 13c, d**) for effective radio-masking and electromagnetic compatibility have been developed with the use of graphene [**11**]. The project manager is Ph.D. Vladimir V. Kolesov (**Fig. 13b**), Head of the Laboratory of Physical Properties of Nanocomposite Materials for Information Technology. Publications in Journals: J. Commun. Technol. Electron., Microelectron. Eng., Nanostruct. Mater., Int. J. Mater., Mech. Manuf., J. Nanophotonics, Phys.-Usp., JETP Lett., Neorg. Mater., Radiotekh. Elektron. (Moscow, Russ. Fed.), Radiotekhnika (Moscow), Biomed. Radioelektron., and others.

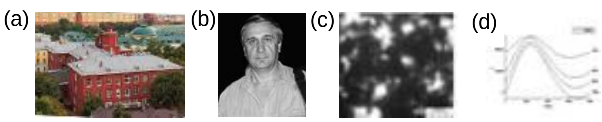

Fig. 13. (a) IRE RAS; (b) Vladimir V. Kolesov; (c) Composite with filler; (d) Absorption of the filler.

In the **Molecular Electronics Research Institute (MERI)**, (http://www.niime.ru), Moscow, Zelenograd (**Fig. 14a**), nanoheterostructures of gallium nitride on silicon substrates (**Fig. 14c**) are being developed. The project manager is Dr. Sc. Eng. Gennady Ya. Krasnikov (**Fig. 14b**), acad. RAS. Publications in Journals: Mikroelektronika, etc.

Fig. 14. (a) MERI; (b) Gennady Ya. Krasnikov; (c) Nitride nanostructures.

Fig. 15. (a) RUDN, (b) Elena F. Sheka.

Researchers at the **Peoples' Friendship University of Russia**, (http://www.rudn.ru), Moscow (**Fig. 15a**), have obtained an explanation of the nanostructured nature of the magnetism of nano-sized graphene, constructed the molecular theory of graphene, and developed the fundamentals of the theoretical chemical physics of graphene. They continue to study the features of the electronic structure of graphene in the light of the general concept of emergent phenomena arising as a result of a quantum phase transition caused by a violation of continuous symmetry [**12**]. The research is carried out in the group of the Dr. Sc. Phys. & Math, prof. Elena F. Sheka (**Fig. 15b**), head of the laboratory of Computational Nanotechnology of Chair of Theoretical Physics and Mechanics of the RUDN. Their work has been published in monographs and such journals as: Mol. Cryst. Liq. Cryst., J. Nanopart. Res., Int. J. Quantum Chem., J. Mol. Model., J. Mater. Chem., Phys.-Usp., J. Exp. Theor. Phys., etc.

AkKo Lab, LLC, (http://www.akkolab.ru), together with the **Scientific-research institute for natural, syntetic diamond and tools** (VNIIalmaz), Moscow (**Fig. 16a**), has developed and announced a thin-film capacitor based on graphene oxide (**Fig. 16c**) with a capacity of 1 mF/cm^2 with an electrode-membrane layer thickness of less than 3 μm [**13**]. The project manager is Dr. Sc. Chem., Prof. Sergey P. Gubin (**Fig. 16b**), scientific header of the AkKo Lab, Head of the Laboratory of Chemistry of Nanomaterials in Kurnakov Institute of General and Inorganic Chemistry of RAS, the organizer and chairman of the first Russian Conference on Graphene "Graphene-Molecule and 2D-Crystal", which became regular, is held every two years in Novosibirsk, Russia (http://grapheneconf.nsu.ru). Publications in Journals: J. Power Sources, Chem. Phys. Lett., Neorg. Mater., and others.

Fig. 16. (a) VNIIalmaz, (b) Sergey P. Gubin, (c) Graphene symmetric supercapacitor.

Researchers at the JSC **Kompozit** (http://www.kompozit-mv.ru) of the State Corporation "Roskosmos", in Korolev, Moscow Region, are developing metal/graphene nanocomposites (such as aluminum/graphene etc.) that include base metal and graphene, dispersed in it, or its variations. Publications in Journals: Int. J. Adv. Mater. Res., Adv. Space Res., Met. Sci. Heat Treat., etc.

At **Carbonlite, LLC**, Dolgoprudny, Moscow Region, a technology has been developed for producing carbon cathode materials for supercapacitors. The project manager is Ph. D. Phys. & Math Semen P. Chervonobrodov, Director. Publications in Journals: J. Power Sources, Chem. Phys. Lett., Carbon, Electrochim. Acta, Electrochemistry (Cambridge, U.K.), Elektrokhimiya, Elektrokhim. Energ., etc.

The **Active-Nano LLC**, (http://www.active-nano.com), St. Petersburg specializes in powder technologies, produces nanostructured powders of micron and submicron sizes up to industrial volumes, produces alloying powders, composite materials, produces experimental parties of MG.

In the **JSC"RPC"Istok" named after A.I. Shokin**", (http://www.istokmw.ru), Fryazino, Moscow Region, nitride nanoheterostructures on silicon substrates have been developed. The project manager is Dr. Sc. Eng. Alexander A. Borisov, Director. Publications in Journals: Radiotekh. Elektron. (Moscow, Russ. Fed.), Radiotekhnika (Moscow), etc.

Conclusion and future perspectives

The report presents a broad information material on the graphene works in Russia. Although the presented picture inevitably does not reflect all the noteworthy results. A wide variety of methods for the synthesis of graphene and graphene-like materials, as well as methods for their diagnostics, was noted. Along with the researches of various properties of graphene, incl. in the field of various radiations (e.g., high-power terahertzic) and experiments with single monolayers, significant results were obtained in the creation of various devices using graphene: from graphene high-frequency transistors, optical, infrared and terahertz radiation receivers, biosensors and fuel cells, up to capacitors and terahertz laser, and also medicines based on polygraphenes. The russian graphene ink for 2D printing technologies of flexible electronics, as well as the aerogels for the electrodes of accumulators and supercapacitors gained international recognition. Graphene nanocomposites were also obtained: from graphene memristors, metal-matrixic composites with graphene dispersed in them or its modifications, up to the nanocomposites for radio masking. A reproducible technology of the development and fabrication of transistors and MIS on wide-gap, nitride nanohetero structures with given parameters has also been created. The technological level reached is in good agreement with the global trends and achievements. This creates the prerequisites for the creation and development of industrial production of graphene and graphene-like materials for use in various fields of science and technology in Russia.

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