

Conditions for the occurrence of Josephson-type current-voltage characteristics in carbon materials at room temperature and normal pressure

Alexander N. Ionov^{1,a}, Alexander N. Bugrov^{2,3,b}

¹Ioffe Institute, St. Petersburg, Russia

²Saint Petersburg Electrotechnical University “LETI”, St. Petersburg, Russia

³NRC “Kurchatov Institute” – PNPI – IMC, St. Petersburg, Russia

^aionov@tuch.ioffe.ru, ^bbugrov.an@mail.ru

Corresponding author: Alexander N. Bugrov, bugrov.an@mail.ru

PACS 74.10.+v, 74.20.Mn, 81.05.ue

ABSTRACT It is shown in the paper that the interaction of highly oriented graphite flakes and graphene films with alkanes is a necessary but insufficient condition for observing the Josephson current-voltage characteristics in them, which is known to be inherent in all superconducting materials. Another key factor is the creation of a deformation field in the graphene material.

KEYWORDS highly oriented pyrolytic graphite, graphene, alkanes, mechanical stresses, superconductivity

ACKNOWLEDGEMENTS We are grateful to Dr. M. S. Dunaevskiy for assistance in studying the surface of HOPG samples.

FOR CITATION Ionov A.N., Bugrov A.N. Conditions for the occurrence of Josephson-type current-voltage characteristics in carbon materials at room temperature and normal pressure. *Nanosystems: Phys. Chem. Math.*, 2026, **17** (3), 297–303.

1. Introduction

The development of materials with room temperature (RT) superconductivity under normal external pressure is a priority area of solid-state physics. RT superconductors have prospect for practical applications in such fields as power engineering, spintronics, medical diagnostics, transportation, etc. [1]. In this regard, the results of Y. Kawashima, published in [2], are of great interest. He observed a reproducible effect of RT superconductivity in flakes of highly oriented pyrolytic graphite (HOPG), exposed to *n*-octane. In the experiment, graphite flakes with an average thickness of ~ 0.01 mm and an average diameter of ~ 1 mm were gently pressed into a Teflon tube with an internal diameter of 1.6 mm and placed in *n*-octane for one day. To obtain proof that graphite flakes treated in this way conduct current without resistance, the Teflon tube was rolled into a continuous ring. After that, a current was created in the ring using electromagnetic induction, which was recorded by a magnetic field sensor for 50 days without noticeable attenuation at room temperature. This fact indicates the absence of electrical resistance in carbon flakes wetted with *n*-octane. RT superconductivity was observed in HOPG flakes only after prolonged soaking in *n*-octane and disappeared when the alkane was removed from them. For this reason, it was proposed to keep the HOPG flakes together with the alkanes in a closed container or using an external pump, maintain the required density of alkane vapors at the location of the carbon material. Y. Kawashima suggested that when alkanes come into contact with graphite flakes, as well as with graphene [3], protons freely moving along the surface of carbon layers without activation energy are generated, which leads to the appearance of the superconductivity effect [4]. Unfortunately, the RT superconductivity effect presented in [2, 4] was not noticed by the scientific community, i.e., it was neither confirmed nor refuted, which significantly slowed down further development of this scientific direction.

In this study, we observed a Josephson-type current-voltage characteristic (CVCs) in carbon materials under normal external pressure and room temperature after their interaction with alkanes, but with the significant addition that a fluctuating strain field must be present within carbon materials. As is known, the Josephson CVCs are one of the main indication of materials with superconducting properties. The Josephson CVCs can be easily distinguished from the ohmic ones which were observed in carbon materials before contact with alkanes.

2. Experimental

The objects of the study were HOPG flakes and graphene films. HOPG (ZYH_DS types) from “TipsNano” (Estonia) was mechanically exfoliated and then ground under ultrasound treatment to linear dimensions close to those used in [2]. Graphene films from “Rusgraphene” (Russia) with a thickness of less than 1 nm and a grain size of over 20 μm were applied to substrates made of copper foil with a thickness of 25 μm and a purity of 99.8 % from “Thermo Scientific” (India), as well as to quartz and silicon with very smooth surfaces.

Graphene films were obtained by chemical vapor deposition (CVD) from a mixture of methane, hydrogen and argon gases on the surface of copper foil. At high temperatures (800 – 1000 °C), methane decomposed into carbon and hydrogen atoms, with copper acting as a catalyst and carbon deposited on the metal surface. Carbon atoms did not diffuse into the copper volume, since the solubility of carbon in copper is very low. It is also important to note that the formation of a second layer of graphene on copper did not occur, since the catalytic activity of copper decreases sharply as it is covered with graphene [5]. Then, some of the graphene films were transferred from copper substrates to smooth silicon with a surface roughness of 0.2 – 0.37 nm and surface frame size of $2 \times 2 \mu\text{m}^2$ and quartz glass surfaces, where the root-mean-square roughness was in the range of 0.6 – 1.3 nm. Due to its high adhesion, graphene readily conforms to the surface of silicon and quartz substrates. It should be noted that several graphene samples after the CVD process remained on the copper after cooling and were not transferred to a new copper substrate, as was the case with quartz and silicon ones. Thus, three types of samples with graphene films were prepared on different substrates: (I) copper, (II) silicon, and (III) quartz.

As is known, an atomic force microscope is the most commonly used tool for studying the graphene surface at the nanoscale [6]. However, our studies showed that the surface roughness height of graphene less than 30 nm does not change the CVCs after contacting graphene with alkanes. This allowed us to use a simpler tool to inspect the surface of graphene, the microinterferometer MII-9 (OJSC “LOMO”, Russia), which made it possible to monitor surface irregularities with a resolution of 28 nm. The graphene surfaces deposited on silicon and quartz glass substrates were characterized by a smooth surface with the accuracy indicated above. However, on the copper substrate, after cooling (from 800 – 1000 °C), the graphene surface had irregularities with heights much larger than 28 nm (up to 80 – 100 nm) due to the significant difference in the thermal expansion coefficients of carbon and copper, which may lead to strain field fluctuations in graphene.

HOPG flakes had linear dimensions up to 1 mm and a thickness of about 0.01 mm, measured with a Mitutoyo 2109A-10 dial indicator (Japan) in steps of 0.001 mm. Their curved surface was visually observed in an MBS-10 type stereo microscope (OJSC “LOMO”, Russia), indicating the presence of irregularities causing deformation field fluctuations in the samples (Fig. 1).

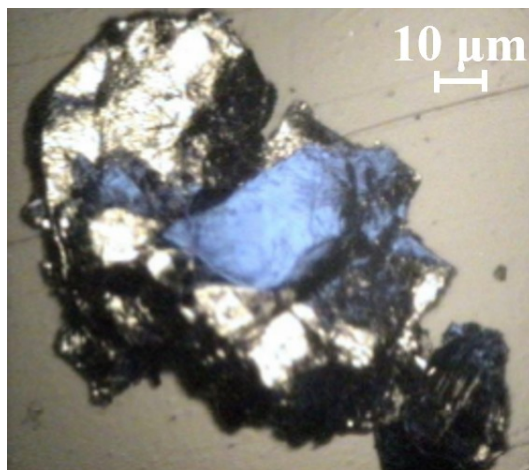


FIG. 1. The image of a single HOPG particle

Measurements of the CVCs of the above samples were carried out in two versions: (a) $I - V$ characteristics of the original sample; (b) $I - V$ characteristics after exposure to alkanes, such as *n*-heptane and *n*-octane. Direct current electrical measurements of the samples were carried out using the four-point probe method in accordance with the standard procedure for materials with metallic conductivity [6]. Current and probe contacts made of silver wires were bonded to the graphene surface using Keller silver-based conductive adhesive. The sample was shielded from extraneous signals. The voltage drop on the probes was measured manually using a digital voltmeter V2-36 (Russia) with an accuracy of $0.01 \mu\text{V}$. In this case, to increase the accuracy of the measurements, with each change in the current, the new voltage value was measured repeatedly relative to the zero current value [6]. The same voltmeter and ammeter were used in different series of experiments, the measurement accuracy of which made it possible to see the difference in the CVCs of different graphene samples before and after contact with alkanes. Our practical experience shows that the presence of noise reduces the voltmeter's sensitivity threshold to 5 nV. In this case, using significantly more accurate instruments is pointless.

3. Results and discussion

The main attention in our work was directed to studying the CVCs type of carbon samples with different surface roughness both before and after their contacts with alkanes. As mentioned above in Y. Kawashima's experiments, due to the high desorption of alkanes from the HOPG flakes, the superconductivity effect disappeared over time, depending on the ambient temperature. In this case, the Josephson CVCs should also gradually transition to ohmic conductivity. For this reason, the CVCs of graphite samples were measured after their direct immersion in alkanes and being kept in it for 24 hours.

Figure 2 shows the CVCs at room temperature and normal pressure for graphene samples on quartz substrate before and after their contacts with *n*-octane. According to the obtained dependences, the treatment of graphene with alkanes did not affect the CVCs in any way, which remained ohmic both before and after the treatment. A similar result was obtained for the Si substrate. These results do not coincide with the statement [3] that after exposure to alkanes, graphene exhibits superconducting properties, which should undoubtedly manifest itself in the appearance of a Josephson CVCs. However, obtained results do not contradict the classical Bardeen–Cooper–Schrieffer theory of superconductivity, according to which the T_c of the transition to the superconducting state should exponentially depend on the density of electron states at the Fermi level.

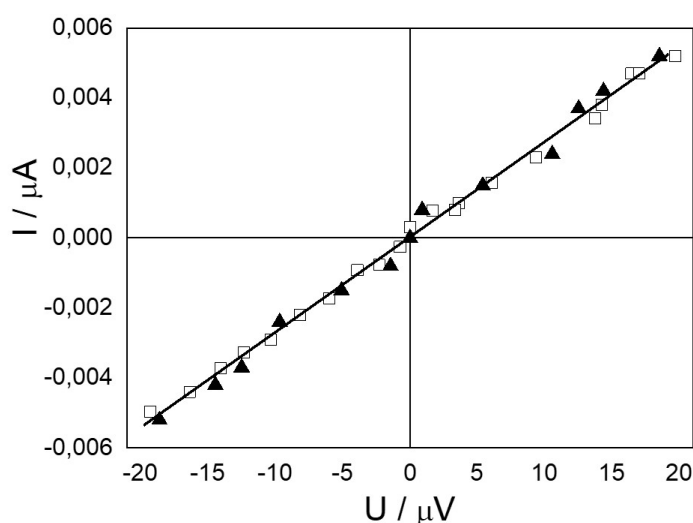


FIG. 2. The CVCs at 300 K and normal pressure for graphene on a quartz substrate without *n*-octan (open square □) and after treatment in *n*-octane (black triangles ▲)

In graphene with smooth surface the energy dependence of the density of states for the conducting and valence zones has the form of cones touching each other with their vertices. Since the valence band is completely filled and the conduction band is empty, it follows that the density of states at the Fermi level is zero. Therefore, within the framework of Y. Kawashima's model, the concentration of protons passing from the homologous series of alkanes to graphene should be negligibly small, which excludes the occurrence of a Josephson CVCs in graphene at room temperature and is consistent with the observation of ohmic ones in our experiments (Fig. 2).

However, the CVCs of HOPG flakes at room temperature, turned out to be not so simple and unambiguous. The experiment showed that the CVCs of less than 0.01 mm thick HOPG flakes which have curvature defects acquired a pronounced Josephson type after contact with *n*-heptane (Fig. 3). In the latter case, at currents below the critical one ($I < \pm I_c$), the voltage drops across the sample was not recorded at normal external pressure and room temperature. This technical zero resistance is in good agreement with the result obtained in [2], where the current was recorded for 50 days in HOPG flakes without noticeable attenuation at room temperature, indicating a superconducting effect. As can be seen from Fig. 2, at a current of 0.001 μA , the voltmeter already records a voltage drop, unlike Figure 3, where a voltage drop is not recorded at a current 100 times greater.

The Josephson CVCs transformed into the ohmic ones in the magnetic field $H = 5.3$ kOe. The effect was reversible i.e. when the magnetic field was switched off, the CVCs of Josephson type were restored again. This behavior of CVCs in a magnetic field is typical for superconducting materials and indicates the complete suppression of superconducting properties ($I_c = 0$) at a certain critical value of H_c , which in our case is ca. 6 kOe. At $H < H_c$, Josephson CVCs are again observed, but with $I < I_c$. After the removal of alkanes from the interlayer space of HOPG flakes upon heating, the Josephson CVCs were irreversibly transformed into ohmic ones. At room temperature in air, the Josephson CVCs was transformed into an ohmic-type within 24 hours. These results are also consistent with those of Y. Kawashima [2],

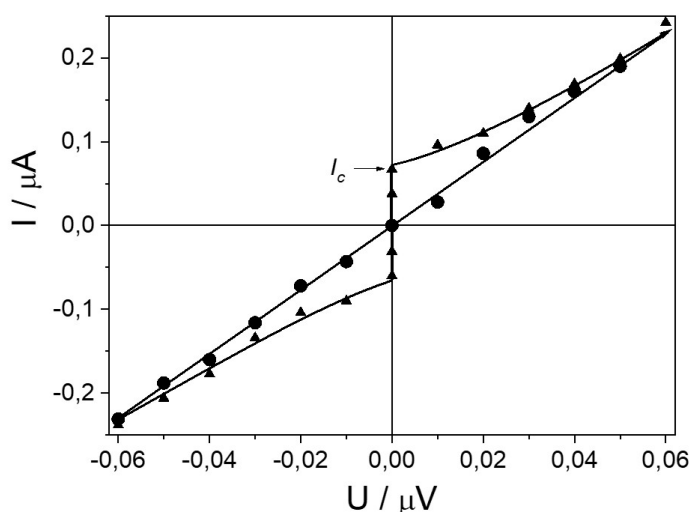


FIG. 3. The CVCs of HOPG flakes after wetting in *n*-heptane at normal pressure and 300 K without magnetic field (black triangles ▲), as well as at $H = 5.3$ kOe (black circles ●)

that superconductivity is observed in HOPG flakes only when in direct contact with *n*-octane. Otherwise, due to the high desorption of *n*-octane from the HOPG flakes, the superconductivity disappeared over a time period dependent on the ambient temperature.

If the strain field in graphene influences the shape of the CVCs, this can be observed in graphene deposited on copper substrates with high surface roughness after wetting them in *n*-octane. The CVCs of a graphene sample on a copper substrate at normal pressure and room temperature after (■) and before (▲) treatment with *n*-octane is presented in Fig. 4. In the first case (Fig. 4, black square ■), graphene does indeed demonstrate a Josephson CVCs with $I_c \approx 24 \mu\text{A}$, while at 10 nV, the conductivity of graphene with $I \approx 25 \mu\text{A}$ is significantly higher than the conductivity ($I \approx 12 \mu\text{A}$) of a copper strip 25 μm thick. Even without taking into account the Josephson CVCs, this result is of great interest for various practical applications. At currents $I < 24 \mu\text{A}$, a technical zero resistance is observed due to a sharp voltage drop across the graphene sheet on the copper substrate, which becomes significantly lower than the voltmeter sensitivity. The Josephson CVCs of graphene sheet on a copper substrate are consistent with the RT superconductivity effect observed in HOPG flakes exposed to *n*-octane [2]. At current $I > 40 \mu\text{A}$ Josephson CVCs in graphene were completely suppressed and the electrical resistance of graphene on copper substrate was shunted by the copper substrate resistance (Fig. 4, black triangles ▲). It should be noted that after heating to 100 °C and cooling to room temperature, the Josephson CVCs of graphene disappear and an ohmic CVCs due to the copper substrate in the experiment is observed (Fig. 4, black triangles ▲).

We suggest that the cause of superconductivity in HOPG flakes, graphene on copper substrate as well as in hybrid particles based on polystyrene and multilayer reduced graphene oxide, may be of the same nature [6, 7]. As mentioned above, the graphene surface on the copper substrate had irregularities significantly greater than 28 nm in height.

The formation of folds during the deposition of graphene layers on substrates leads to the appearance of pseudomagnetic fields, which increase the density of states in graphene [8–10]. In strong pseudomagnetic fields, the density of states of graphene is transformed into flat bands [11–14], which, upon contact with alkanes, are filled with current carriers. According to theoretical calculations, flat bands can radically increase the density of states in localized regions of a carbon material. This leads to the creation of a discrete spectrum of levels within such regions, analogous to Landau levels, and can also facilitate the emergence of superconductivity [9–12], which in our case manifests itself in the Josephson CVCs.

In HOPG, superconductivity can be caused by linear and rhombohedral stacking faults in graphene layers, which arise during their bending, twisting, cleavage, perforation, and other mechanical influences [15]. Fluctuating strain fields lead to the formation of flat bands in the density of graphene sheet states [13, 14]. When in contact with alkanes, HOPG flakes, consisting of mechanically deformed graphene sheets, saturate the interlayer space with charge carriers and, in the presence of flat bands, induce superconductivity.

As our experiment showed, in HOPG flakes pre-crushed to several micrometers (Fig. 5), no Josephson CVC was observed after their contact with alkanes (Fig. 6). Only the ohmic volt-ampere characteristics were observed, which can be explained by the disappearance of the fluctuation field of deformation inside individual graphite flakes as their sizes decreased.

As for bulk HOPG samples with a thickness significantly greater than 0.01 mm, the behaviour here is not unambiguous. On the one hand, in individual HOPG samples at room temperature and normal external pressure, research groups

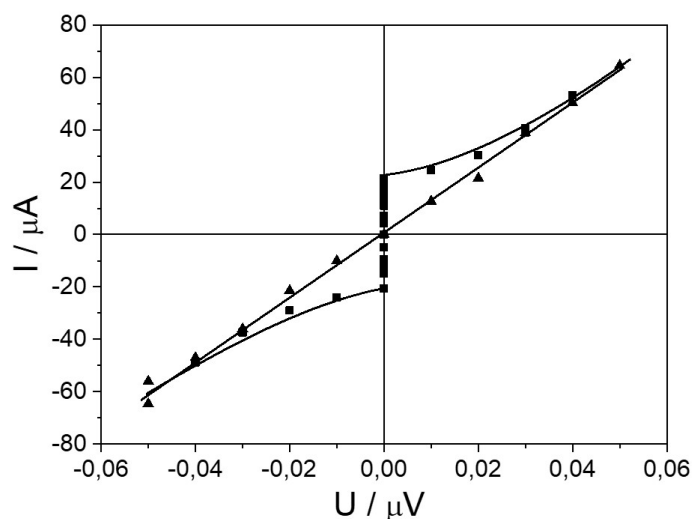


FIG. 4. The CVCs measured for a graphene sheet on a copper substrate 0.8 cm wide and 25×10^{-4} cm thick after (black square ■) and before (black triangles ▲) exposure to *n*-octane. The distance between voltage contacts was ca. 0.8 cm

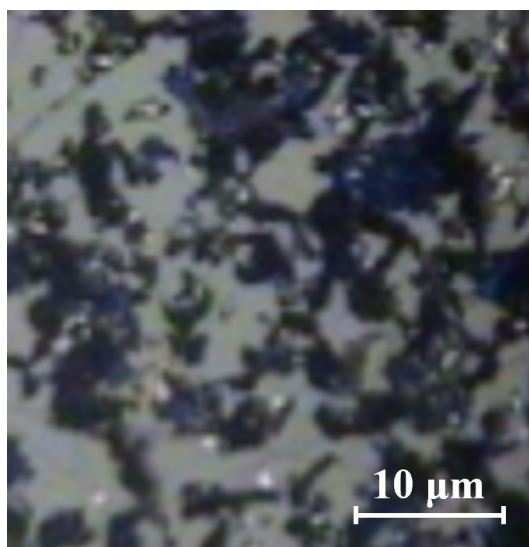


FIG. 5. The image of pre-crushed HOPG flakes

from all over the world observed effects characteristic of type II superconductors [16–21]. On the other hand, many other visually identical HOPG samples did not exhibit RT superconductivity effects. Thus, the observed RT superconductivity in bulk HOPG samples, for unclear reasons, turned out to be technologically uncontrollable, which excluded their practical applications. It should be noted here that curvature defects are impossible in bulk HOPG samples of large thickness. However, if various crystalline phases are present in bulk HOPG samples in a random, uncontrolled manner [18], lattice defects can form. According to the theoretical model proposed in [22], strong fluctuations of the strain gradient can form local drops of Bose condensed superconducting pairs in bulk HOPG samples. If the droplets are small enough, the theoretical model predicts a high critical temperature for superconductivity [22]. Bulk superconductivity can be achieved by tunnelling from one droplet to the neighbouring one. In the proposed model, superconductivity can arise randomly not through external doping with charge carriers, as in the cases discussed above, but through the internal redistribution of charge carriers within a bulk HOPG sample.

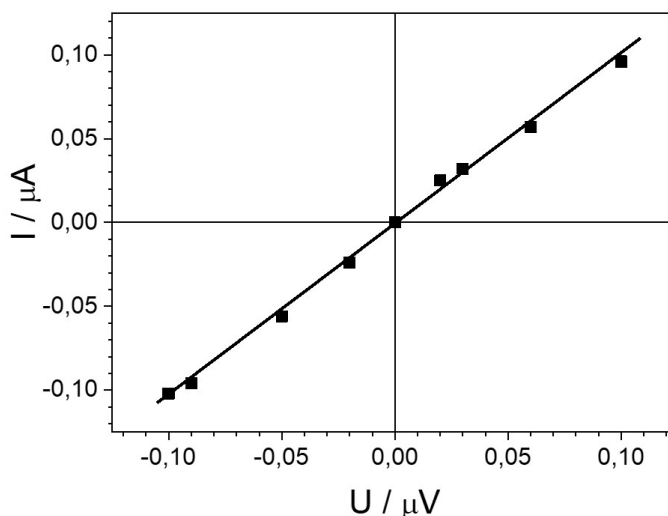


FIG. 6. The CVCs of HOPG flakes pre-crushed to several micrometers after wetting in *n*-heptane at normal pressure and 300 K

4. Conclusions

The correlations shown in this paper between carbon materials with different surface roughness and types of CVCs after their contact with alkanes, clarifies Kawashima's study. Similarly, the deformation of multilayer RGO sheets functionalized with methacrylate groups and copolymerized with styrene after contact with aromatic hydrocarbons (e.g., toluene) in a cross-linked structure, which was examined in our earlier studies, also resulted in the appearance of Josephson CVCs up to room temperature under normal pressure [6, 23, 24]. The Josephson CVCs is consistent with the observed magnetization corresponding to a type II superconductor, whose superconductivity is completely suppressed in a magnetic field ($H > 3$ kOe) [25, 26]. This sample behavior in a magnetic field is consistent with both the literature data [6] and the result of the present work, where it was shown that the Josephson CVCs are completely suppressed by a magnetic field of the same order of strength.

Research in this direction may be important for technological progress in obtaining materials with RT superconductivity and may significantly influence the development of both the theory and practical applications of superconductivity.

References

- [1] Coombs T.A., Wang Q., Shah A., Hu J., Hao L., Patel I., Wei H., Wu Y., Coombs T., Wang W. High-temperature superconductors and their large-scale applications. *Nat. Rev. Electr. Eng.*, 2024, **1** (12), P. 788–801.
- [2] Kawashima Y. Possible room temperature superconductivity in conductors obtained by bringing alkanes into contact with a graphite surface. *AIP Adv.*, 2013, **3**, 052132.
- [3] Geim A.K., Novoselov K.S. The rise of graphene. *Nature Materials*, 2007, **6**, P. 183–191.
- [4] Kawashima Y., U.S. Patent, 2011/0130292 A1.
- [5] Rusakov P.S., Kondrashov I.I., Rybin M.G., Pozharov A.S., Obraztsova E.D. Chemical vapor deposition of graphene on copper foils. *J. of Nanoelectronics and Optoelectronics*, 2013, **8** (1), P. 79–82.
- [6] Ionov A.N., Ankudinov A.V., Nikolaeva M.N., Bugrov A.N. Josephson type current-voltage characteristics of chemically modified graphite at room temperature and normal pressure. *Technical Physics Letters*, 2024, **50** (10), P. 9–12.
- [7] Nikolaeva M.N., Bugrov A.N., Anan'eva T.D., Gushchina E.V., Dunaevskii M.S., Dideikin A.T. Resistance of reduced graphene oxide on polystyrene surface. *Nanosystems: Physics, Chemistry, Mathematics*, 2018, **9** (4), P. 496–499.
- [8] Guinea F., Horowitz B., Le Doussal P. Gauge field induced by ripples in graphene. *Phys. Rev. B*, 2008, **77**, 205421-8.
- [9] Vozmediano M.A.H., Katsnelson M.I., Guinea F. Gauge fields in graphene. *Phys. Rep.*, 2010, **496** (4-5), P. 109–148.
- [10] Neek-Amal, M.; Peeters, F. M. Strain-engineered graphene through a nanostructured substrate. I. Deformations. *Phys. Rev. B*, 2012, **85** (19), 195446.
- [11] Levy N., Burke S.A., Meaker K.L., Panlasigui M., Zettl A., Guinea F., Castro Neto A.H., Crommie M.F. Strain-induced pseudo-magnetic fields greater than 300 tesla in graphene nanobubbles. *Science*, 2010, **329** (5991), P. 544–547.
- [12] Uchoa B., Barlas Y. Superconducting states in pseudo-Landau-levels of strained graphene. *Phys. Rev. Lett.*, 2013, **111**, 046604.
- [13] Castro-Villareal P., Ruiz-Sanchez R. Active motion on curved surfaces. *Phys. Rev. B*, 2018, **97**, 052605.
- [14] Liu L.-C. Pseudo-magnetic fields of strongly-curved graphene nanobubbles. *Int. Jour. Mod. Phys. B*, 2018, **32** (11), 1850137.
- [15] Trugenberger C.A. Room-temperature superconductivity in 1D. *Condens. Matter.*, 2024, **9** (3), 34.
- [16] Esquinazi P., García N., Barzola-Quicuia J., Röddiger P., Schindler K., Yao J.-L., Ziese M. Indications for intrinsic superconductivity in highly oriented pyrolytic graphite. *Phys. Rev. B*, 2008, **78**, 134516.
- [17] Ballestar A., Barzola-Quicuia J., Scheike T., Esquinazi P. Josephson-coupled superconducting regions embedded at the interfaces of highly oriented pyrolytic graphite. *New J. Phys.*, 2013, **15**, 023024.

- [18] Zoraghi M., Barzola-Quiquia J., Stiller M., Setzer A., Esquinazi P., Kloess G.H., Muenster T., Lühmann T., Estrela-Lopis I. Influence of rhombohedral stacking order in the electrical resistance of bulk and mesoscopic graphite. *Phys. Rev. B*, 2017, **95**, 045308.
- [19] Saad M., Gilmutdinov I.F., Kiiamov A.G., Tayurskii D.A., Nikitin S.I., Yusupov R.V. Observation of persistent currents in finely dispersed pyrolytic graphite. *JETP Lett.*, 2018, **107**, P. 37–41.
- [20] Lebedev S.G. Traces of superconducting correlations in nanographite films. *J. Mater. Sci.: Mater. Electron*, 2020, **31** (2), 20883.
- [21] Esquinazi P.D., Lysogorskiy Y.V. (2016) Experimental evidence for the existence of interfaces in graphite and their relation to the observed metallic and superconducting behavior. In: Esquinazi P. (Ed.), *Basic physics of functionalized graphite*. Springer International Publishing, Switzerland, P. 145–179.
- [22] Kopelevich Y., Torres J., da Silva R., Oliveira F., Diamantini M.C., Trugenberger C., Vinokur V. Global room-temperature superconductivity in graphite. *Adv. Quantum Technol.*, 2024, **7**, 2300230.
- [23] Ionov A.N. Josephson current-voltage characteristic of a composite based on polystyrene and graphene oxide. *Tech. Phys. Lett.*, 2015, **41**, P. 651–653.
- [24] Ionov A.N. Josephson-like behaviour of the current–voltage characteristics of multi-graphene flakes embedded in polystyrene. *J. Low Temp. Phys.*, 2016, **185**, P. 515–521.
- [25] Ionov A.N., Volkov M.P., Nikolaeva M.N., Smyslov R.Y., Bugrov A.N. The magnetization of a composite based on reduced graphene oxide and polystyrene. *Nanomaterials*, 2021, **11** (2), 403.
- [26] Ionov A.N., Volkov M.P., Nikolaeva M.N., Smyslov R.Y., Bugrov A.N. Magnetization of ultraviolet-reduced graphene oxide flakes in composites based on polystyrene. *Materials*, 2021, **14** (10), 2519.

Submitted 16 January 2026; revised 14 May 2026; accepted 17 May 2026

Information about the authors:

Alexander Nikolaevich Ionov – Ioffe Institute, St. Petersburg, 194021, Russia (<https://journals.ioffe.ru/en>); ORCID: 0000-0002-5207-2642; ionov@tuch.ioffe.ru

Alexander Nikolaevich Bugrov – Branch of Petersburg Nuclear Physics Institute named by B.P. Konstantinov of National Research Centre “Kurchatov Institute” – Institute of Macromolecular Compounds, St. Petersburg, 199004, Russia; Department of Physical Chemistry, Saint Petersburg Electrotechnical University (ETU “LETI”), St. Petersburg, 197022, Russia; ORCID 0000-0003-1052-4919; bugrov.an@mail.ru

Conflict of interest: the authors declare no conflict of interest.