

R & D on carbon nanostructures in Russia: scientometric analysis, 1990–2011

Alexander I. Terekhov

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Abstract The analysis, based on scientific publications and patents, was conducted to form an understanding of the overall scientific and technology landscape in the field of carbon nanostructures and determine Russia's place on it. The scientific publications came from the Science Citation Index Expanded database (DB SCIE); the patent information was extracted from databases of the United States Patent and Trade Office (USPTO), the World Intellectual Property Organization (WIPO), and Russian Federal Service for Intellectual Property (Rospatent). We used also data about research projects, obtained via information systems of the U.S. National Science Foundation (NSF) and the Russian Foundation for Basic Research (RFBR). Bibliometric methods are used to rank countries, institutions, and scientists, contributing to the carbon nanostructures research. We analyze the current state and trends of the research in Russia as compared to other countries, and the contribution and impact of its institutions, especially research of the "highest quality." Considerable focus is on research collaboration and its relationship with citation impact. Patent datasets are used to determine the composition of participants of innovative processes and international patent activity of Russian inventors in the field,

and to identify the most active representatives of small and medium business and some technological developments ripe for commercialization. The article contains a critical analysis of the findings, including a policy discussion of the country's scientific authorities.

Keywords Nanotechnology · Carbon nanostructures · Bibliometric analysis · Research collaboration · Patent analysis · Commercialization

Introduction

Carbon nanostructures have played a critical role in the development of nanotechnology. New forms of carbon, such as fullerenes, nanotubes, and graphene, have attracted a huge research interests and led to two Nobel Prizes. Nobelist H.W. Kroto (2014) believes that the discovery of fullerenes in 1985 and then carbon nanotubes (CNTs) in 1991 catalyzed the birth of nanoscience and nanotechnology. According to two other experts Ozawa and Osawa (2006), if it were not for these discoveries, the coming of nanotechnology might have been delayed by at least for a few decades. Kostoff et al. (2006) in their extensive bibliometric study noticed that based simply on the publication counts, modern nanotechnology development has proceeded along two major technology thrusts: nanotubes and the other nanotechnologies. We add that by

A. I. Terekhov (✉)
Central Economics and Mathematics Institute of the
Russian Academy of Sciences, Nakhimovsky Avenue 47,
117418 Moscow, Russia
e-mail: a.i.terekhov@mail.ru

the number of received citations, the publications, which report on the discovery of fullerene, nanotube and graphene (Kroto et al. 1985; Iijima 1991; Novoselov et al. 2004) are among the Top 100 publications of DB SCIE. Herewith (Iijima 1991) ascended from 33rd at 16th place from December 2011 to December 2012, and (Novoselov et al. 2004) flew up from 83rd at 47th place from December 2012 to December 2013. Despite some disappointment due to the difficulties of commercialization (Noorden 2011), carbon nanostructures remain on the agenda in a wide range of applications in such large sectors, as nanoelectronics, nanobiotechnology, and nanoenergy (Volder et al. 2013; Novoselov et al. 2012; Mochalin et al. 2012). Such a high significance for the nanotechnology development, as well as huge socio-economic expectation has attracted the attention of social scientists and, above all, scientometric investigators to carbon nanostructures.

However, it appeared that even the large-scale scientometric studies on nanotechnology (Kostoff et al. 2006; Porter et al. 2008; Huang et al. 2011; Arora et al. 2013) are not able to comprehend this field enough holistically. This stimulated corresponding carbon-oriented studies. Remarkable that the boom of carbon nanostructures has begun a decade before the initiative in nanotechnology was adopted on national scales. Hence, a deeper analysis of its already gained experience is of special value. It helps to better understand the processes of production and transfer of advanced scientific knowledge and nature of nanotechnology innovation; to recognize the extent of initial nano-hype; and to make the corrections in nanotechnology politics.

Braun (1992) first drew attention to an epidemic character of spread the fullerene research since 1985.¹ Sufficiently detailed bibliometric analysis of developing the fullerene research in the period 1985–1998, using data from the Science Citation Index and the Engineering Compendex, was presented in Braun et al. (2000) and Kostoff et al. (2000). In the first study, the dissertation literature on the topic was used, and in the second, bibliometrics was combined with procedures of

a textual database analysis. Interestingly, both studies noticed that a large number of fullerene researchers fully focused on CNTs. Deeper study, using network analysis, showed despite a genetic relationship, nanotube research has apparently acquired its own dynamics soon after their discovery and has been disconnected from fullerene research (Lucio-Arias and Leydesdorff 2007). In Marx and Barth (2010), it was shown that since 2000 CNTs have supplanted previously more promising fullerenes, and the scientific literature on nanotubes became to grow exponentially. This study provides bibliometric analysis of nanotube research, using the databases and the analytical tools of the Web of Science (WOS) and the Chemical Abstracts Service (CAS).

After the experimental discovery of graphene in 2004, a rapidly growing stream of scientific literature, dedicated to this new “rising star,” became the subject for the study by bibliometric methods (Barth and Marx 2008; Shapira et al. 2010; Lv et al. 2011). These studies use different data sources (WOS, CAS and Information Services for Physics, Electronics, and Computing) in order to evaluate global scientific production and developing trend of graphene research via bibliometric analysis and knowledge visualization technology. A number of works, in one way or another, provide comparisons within the “starry triad”: fullerenes–nanotubes–graphene (Barth and Marx 2008; Plume 2010; Noorden 2011; Milanez et al. 2013). So, Milanez et al. (2013) exploit analytical tools of the WOS for studying the research trends and publications on fullerenes, CNTs, and graphene as well as revealing the main global players and journals in the period 2001–2010. A short essay on the basis of the Scopus database (Plume 2010) notices that although research communities inside the “triad” are well interconnected vessels, nonetheless A.K. Geim and K.S. Novoselov, who have made the biggest contribution to the field of graphene, had no background in CNTs or fullerenes.

Information, which is useful for comprehensive analysis in such science-technology fields as the carbon nanostructures, is contained also in the patent literature. In some of above-mentioned studies, bibliometric analysis has already been complemented by analysis of patent data, for example, from the CAS database and the Derwent Innovation Index database (Marx and Barth 2010; Lv et al. 2011). Individual representatives and the entire “triad” in general have become objects for specialized patent

¹ At the initiative of T. Braun in 1994 the international journal “Fullerene Science and Technology” (“Fullerenes, Nanotubes and Carbon Nanostructures” since 2002) was established that undoubtedly contributed to the development of fullerene science.

studies (Miller and Harris 2006; Michalitsch et al. 2008; Pham and Fayerberg 2011; McDermot Will and Emery 2014). Thus, the carbon nanostructures as a very important part of nanoscience and nanotechnology became a self-sustained subject for scientometric studies.

Specific experiences and contribution of individual countries to the development of the major directions in nanotechnology are of interest for science researchers as well as for informed policy making. The search for (and study of) new forms of carbon in Russia has deep historical roots as well as a number of successful episodes. So, in the early 1970s, the computational justification of stability of molecule C60 in the form of a truncated icosahedron was given at the Institute of Organoelement Compounds of the Academy of Sciences of the USSR (Bochvar and Gal'pern 1973). However, then this excellent result has not received further development and support. In 1952, Soviet scientists from the Institute of Physical Chemistry of the Academy of Sciences of the USSR first observed CNTs in an electron microscope. Fibers with a diameter of ~ 100 nm with hollow channels and endings filled with metal have been obtained by thermal decomposition of carbon monoxide on an iron catalyst. In this area, the research also has not been continued. Besides, the article describing this observation was published in Russian in a Soviet journal (Radushkevich and Lukyanovich 1952) and was not easily accessible to Western scientists. Russian scientists have once again turned to the subject of CNTs only in the early 1990s (Chernozatonskii 1992). Note that in 2004, a key contribution to the discovery of graphene was made by former and current Russian scientists from the Institute of Microelectronics Technology and High Purity Materials (IMT) of the Russian Academy of Sciences (RAS) (Novoselov et al. 2004). More details can be found in (Vul and Sokolov 2009).

It is appropriate add that, in response to the global fullerene boom, which erupted in the early-1990s, Russia organized the "Fullerenes and atomic clusters" research activity in 1993. The activity was conducted as an element of the "Actual Directions in Condensed Matter Physics" state scientific-technical program. This project helped the country form a research community for studying fullerenes and other carbon nanostructures, through support of several tens of research teams. Subsequently, the carbon-based

direction became one of the principal components of the Russian nanotechnology program.

Meanwhile, developing of R & D in the field of carbon nanostructures in Russia has not been specifically studied. In relevant foreign studies (Kostoff et al. 2000; Braun et al. 2000; Marx and Barth 2010; Milanez et al. 2013), mentions of Russia as well as RAS, usually do not extend beyond international rankings based on publications production. As for patents, information is even more scarce. For example, according to Michalitsch et al. (2008), 5 % of all fullerene-related patent applications filed in European Patent Office by 2006, originated from Russia. In domestic scientometric literature, the comprehensive analyses devoted to the carbon nanostructures are also absent. Those that exist (Terekhov et al. 2006; Terekhov 2009) only partially touch on this subject. The first work evaluates the current state of fullerene science in Russia, and the second gives a short scientometric analysis of R & D in the field of fullerenes and CNTs under the general theme of fundamental building blocks for nanotechnology.

The aim of this article is to provide a comprehensive analysis relying on the known information resources, including Web of Knowledge, information systems of the NSF, and the RFBR as well as patent databases of the USPTO, WIPO, and Rospatent. Thematically, we focus not only on three "starry" carbon nanostructures, but also on nanodiamond (NDM) and other forms of nanocarbon (OFNC). Choice of carbon nanostructures (in such enlarged understanding)² for special and deeper study is able to add new items into the global picture of nanotechnology development. The choice is also well suited for testing the capability of the national science-technology complexes to operate at the cutting edge of research and to convert their results into commercial applications.

In the first part, we apply bibliometrics to measure the contribution of Russia to the C-nano research, published in peer-reviewed journals. By aggregating obtained bibliometric information across countries and subfields of C-nano, we will track science trends including benchmarking of Russia against the main competitors. Citation analysis will help to characterize

² Further we will use "C-nano" as identifier for the subfield of nanoscience and nanotechnology related to the production and use of carbon nanostructures.

the quality of national research and to identify the research of “highest quality.” By and large, the research of highest quality is the result of research and its assessment by peers. However, the citation-based indicators have been developed and now are widely used as “proxies” for the true scientific quality of publications or scholars. Since co-authorship is most commonly used in bibliometrics as an indicator of collaboration, we pay considerable attention to studying the authorship patterns and the influence of international or domestic co-authorship on research productivity. Finally, we will reveal the key players in C-nano research and define the contribution and impact of Russian institutions and individual scientists.

Patents, in a sense, are indicators of input into the economy, therefore in the second part, we appeal to patent analysis to better understand the economic impacts of C-nano field. In this part, the overall trends of patent activity in studied field are considered. Via the USPTO and WIPO databases, we compare international patent activity of the inventors from Russia and other BRIC countries. Since protection of an invention starts usually with national patent office, we pay much attention to the C-nano patents granted by Rospatent. To date, Rospatent is a modern patent office, which issues annually about 30,000 patents for industrial inventions. Status as the International Searching Authority and the International Preliminary Examining Authority confirms of its recognition in the world. Is pertinent to note, that a systemic adaptation of national legislation in the field of intellectual property (IP) to the market relations has occurred since the collapse of the USSR in the early 1990s in connection with the adoption of the Patent Law of the Russian Federation and the other special laws in this field. In 2008, the Patent Law has lost action and, instead of it the Part IV of the Civil Code of the Russian Federation was introduced to regulate the relations in the field of patent rights. Nowadays, the patent legislation of Russia generally corresponds to the world standards (European Union 2010). In accordance with it, both individuals and legal entities, regardless of property forms may be owners of a patent for invention. The foreign individual persons and legal entities enjoy the rights equally with Russian ones, on the basis of international treaties, in which Russia is party, or on the basis of reciprocity.

Collected patent data refer to the period after upgrading of the Russian patent system and, therefore, are valid. These data will provide a more accurate ascertainment of the level of inventive activity in the field, composition of its participants, and how an implemented policy influences these parameters. Using patent analysis, we will form a more true understanding of the Russia’s technology landscape in C-nano, and also obtain an information about corporate participants in innovation process as and about directions for possible commercialization. Furthermore, the analysis will highlight the problem of still poor integration of the Russian patent system into an innovative environment, when turnover of granted patents and use of IP for innovation development are at a low level.

As a result, we want to reveal the strengths and weaknesses of R & D in carbon nanostructures; to evaluate the performance of Russia in this direction, an important component of national nanotechnology program; and to expand the evidence base for policy decisions. The article ends with the conclusions from the performed scientometric analysis. Since the nanotechnology policy pursued by Russian scientific authorities directly concerns C-nano, we also discuss some of its results and failures in the light of present analysis.

Methodology and data

This study focuses on the period 1990–2011. Its methodology includes first of all development of the keyword list and search strategy. With the help of expert advice and testing in the DB SCIE, we have formed the lexical query with 27 search terms. These are proper keywords, adopted abbreviations, and characteristic chemical formulas (Appendix A). Our approach to the operational definition of the C-nano field is a unifying and most comprehensive in comparison with those previously used. So, the most extensive nanotechnology/nanoscience-focused studies of general character (Kostoff et al. 2006; Porter et al. 2008; Arora et al. 2013) do not use, for example, such terms from our list as: “C70 or C-70”, “fullerid*,” “fullerit*,” “fullero*,” “azafulleren*,” and “buckytub*.” Other terms from our list (“nanodiamond*,” “nanopor*,” and “nanocarbon*”) appear in these works only as part of the total array of

nano-terms, not highlighting the C-nano field. Finally, this list terminologically exceeds the search queries of known special studies: in fullerenes and its derivatives (Kostoff et al. 2000; Braun et al. 2000); in CNTs (Barth and Marx 2008; Milanez et al. 2013); and in graphene (Marx and Barth 2010; Shapira et al. 2010; Lv et al. 2011). For example, in the last case we added the relatively new term: “graphane*.”

We chose the DB SCIE, because it is international multidisciplinary database that includes more than 31.3 million scientific publications (articles, reviews, letters, proceeding papers, and etc.) in peer-reviewed journals. From year 1990 until the moment of this study in December 2012, Russia (USSR until 1992) is represented in the database by about 662,300 publications that put it at tenth place among all countries. Feature of projects is that they are selected on a competitive basis from the research proposals submitted in funding organizations, and their result may be several thematic scientific publications. Since the projects databases of the NSF (www.nsf.gov/awardsearch) and the RFBR (www.rfbr.ru) are extensive and covering a wide spectrum of disciplines, we chose them for benchmarking the structure of Russian C-nano research compared with American ones at the end of the study period. We took into account the projects by year of start and did not consider awards of the type of “fellowship” or “publishing grants.” Three sources of patent information were used, two of which are the well-known patent databases: DB PatFT of the USPTO (www.uspto.gov) and DB PATENTSCOPE of the WIPO (www.wipo.int). It should be noted that in DB PATENTSCOPE we will deal essentially with international patent applications within the framework of the Patent Cooperation Treaty (PCT), so that hereinafter the term “WIPO patent” will refer to patent filed under PCT, but not to granted patent. Database RUPAT of the Rospatent is much less known. We used this database of patent abstracts (www.rupto.ru) for search in both English and Russian versions.

Lexical search in the titles has identified 85,987 relevant C- nano publications in the DB SCIE for the period 1990–2011 as well as 274 research projects in the NSF database and 139 projects in the RFBR database over the period 2007–2011. We used more broad criterion for selection of C-nano patents: a patent is considered relevant, if there is at least one keyword in its title or abstract. With this “title–

abstract” search, we selected 3,105 patents from the DB PatFT, 3,640 patents from DB PATENTSCOPE, and 555 patents from the DB RUPAT. These six formed datasets became sources for our analysis.

Bibliometric analysis is based on traditional indicators (publication counts or citations, Hirsch index (H-index), measures of collaboration, and etc.), which an easily obtained for various subsets of the initial bibliographic dataset via services of Web of Knowledge. We will use them, but adding more skillful indicators: collaborative coefficient (CC) to measure the degree of collaboration in research; so-called “crown” indicator for citation-based research performance evaluations. CC has been developed by Ajiferuke et al. (1988) in response to the shortcomings of such simple measures as mean number of authors per paper and degree of collaboration. It is given by

$$1 - \frac{1}{n} \sum_{j=1}^A \frac{1}{j} f(j),$$

where n denotes the number of publications, $f(j)$ denotes the number of j -authored publications, and A denotes the greatest number of authors per publication in this sample. “Crown” indicator was developed in Centre for Science and Technology Studies of Leiden University for normalization of the citation counts, given the differences among fields (Waltman et al. 2011). We used CPP/FCSm (citations per publication/mean field citation score) indicator, which is defined as:

$$\text{CPP/FCSm} = \frac{\sum_{i=1}^{i=n} c_i}{\sum_{i=1}^{i=n} e_i},$$

where n denotes the same as above, c_i denotes the actual number of citations of publication i , and e_i denotes the expected number of citations of publication i , given the field in which publication i has been published. In the case of overlapping subfields, we used in calculations the rule of arithmetic average.

To estimate relationship between impact and the number of authors of publications, we apply regression analysis. For evaluative bibliometrics, it is characteristic to seek to identify the research of “highest quality.” This is why the article uses not only bibliometric impact scores based on average values, but also indicators reflecting the top of the citation distribution. Additionally, a certain preparation of

initial data was required, for example, at preliminary stage we eliminated the ambiguity of names for Russian organizations as well as authors of publications in the DB SCIE to achieve more accurate estimates at the micro-level. We also took into account the peculiarities of affiliation of local research institutes, in particular, in calculating the aggregate ratings for RAS.

An analysis using the project datasets will allow farther look at the situation through the prism of research teams' thematic preferences in C-nano. Extracted patent datasets will be subjected to statistical analysis with the aim:

- to measure the level and dynamics of inventive activity in Russia;
- to describe a rising technology landscape in C-nano; and
- to estimate the Russia's weight as player in C-nano innovation and to compare its weight against its economic peers in BRIC.

Finally, we used the combined search in the databases jointly with the information from web-sites as a method to identify members of corporate sector that are active in C-nano, and their production specialization. Thus, the multiplicity of information sources, approach to forming the relevant datasets and the diversity of applied analytical methods are designed to provide of a comprehensive methodology for studying the development of C-nano field in Russia and in the world.

Bibliometric analysis of C-nano research

Publication trends and citation impact: country level

Scientists from more than 100 countries have participated in research work in the C-nano. According to Fig. 1, the productivity of research activity in this field has continued to expand, reaching 13,164 publications in 2011. Since 2000, output has increased 6.5 times, which is slightly greater than the growth of all nano publications (6.2 times) and far greater than the growth of all scientific literature in DB SCIE for the same period (~1.6 times). Table 1 demonstrates a very intensive buildup of Asian countries' research activity in C-nano, which has brought about significant

changes in their ranking. By 2010, China had become the world leader, surpassing the USA. South Korea, for its part, had risen from 11th place in 2000 to third-place in 2011, even overtaking Japan. Finally, India and Singapore climbed 11 places to reach 6th and 12th place, respectively. It is interesting to note that Iran, starting from scratch, has risen in the same time span to 7th place. Brazil, a member of BRIC, has moved from 25th to 17th place. At the same time, many Western countries have decreased in ranking as follows: France (6↓8), the UK (7↓9), Italy (8↓14), Spain (9↓13), Belgium (10↓20), Switzerland (12↓21), and Sweden (15–16↓18–19).

Russia's share in the global output of C-nano publications from 1990 to 2011 is 5.5 %, corresponding to sixth place. However, between 2000 and 2011, it fell from 4th to 10th place. According to Fig. 2, Russia has the worst competitive position in research on CNTs and graphene. By contrast, it manages to hold high places in studies of NDM and fullerenes.

Information extracting from research projects serves as another means of grasping the structure and dynamics of C-nano research. As established in our previous research (Terekhov 2007), by frequency of occurrence in the titles of RFBR's nano-projects for 1993–2006, the term “fullerene” was second after the term “nanostructure”.³ In the subsequent five-year period, fullerenes gave way to CNTs in attracting the interest of Russian research groups (Fig. 3). By comparison, the structure of these interests differs significantly from those in the U.S. (Fig. 3). Figures 2 and 3 reveal the “conservative” specificity of Russian scientists research in the C-nano field.

The quality of the produced publications, rather than their number, plays an important role in science competition. In bibliometrics, citation impact is a fair component of qualitative analysis. Figure 4 confirms the exponential growth (epidemic spread) of research in C-nano, the main contribution to which since 2006 belongs to CNTs. According to Table 2, Russia is in 9th place globally in terms of citations to its C-nano publications. But it occupies only 36th place among 46

³ Add a number of international projects in the field of C-nano funded in those years by the International Science and Technology Centre. For example: Project No. 079 “Fullerenes” (Leading Institute: Research Institute “Graphite”, Moscow), Project No. 3088 “Fullerene-Oxygen-Iodine Laser” (Research Institute for Laser Physics, St. Petersburg) and others.

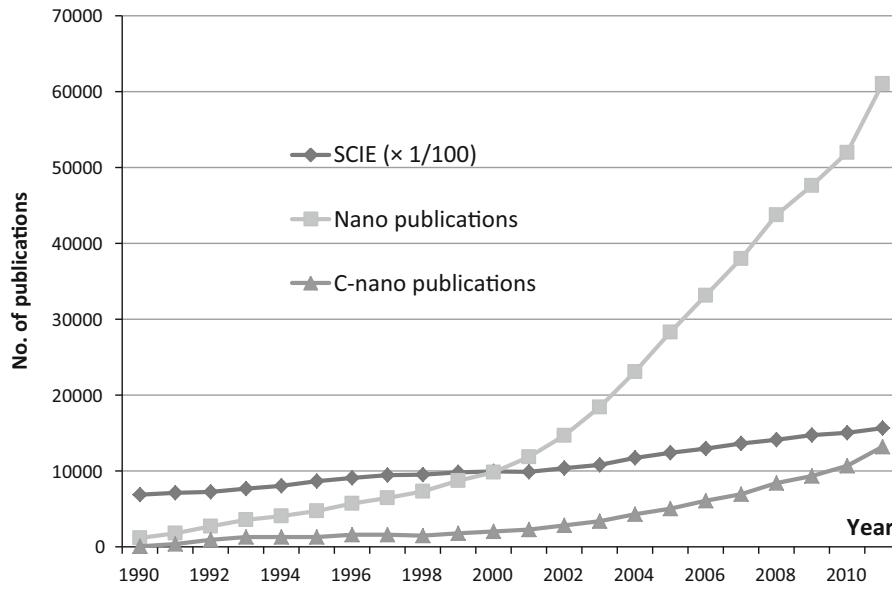


Fig. 1 Scientific literature time evolution (DB SCIE), 1990–2011

Table 1 Ranking countries by the number of C-nano publications

Country	No. of C-nano publications			Rank		
	2000	2011	1990–2011	2000	2011	1990–2011
USA	531	2,821	22,579	1	2	1
China	268	3,789	17,937	3	1	2
Japan	383	1,053	10,532	2	4	3
Germany	156	734	5,924	5	5	4
South Korea	47	1,147	5,159	11	3	5
Russia ^a	223	434	4,735	4	10	6
UK	109	504	4,148	7	9	7
France	144	505	4,114	6	8	8
Italy	85	348	2,529	8	14	9
India	32	557	2,398	17	6	10
Taiwan	35	424	2,324	15–16	11	11
Spain	53	385	2,184	9	13	12
Canada	31	296	1,682	18	16	13
Singapore	25	402	1,512	23	12	14
Iran	0	535	1,427	–	7	15
Australia	26	313	1,414	21	15	16
Switzerland	46	137	1,253	12	21	17
Belgium	49	147	1,165	10	20	18
Poland	45	154	1,070	13	18–19	19
Sweden	35	154	1,050	15–16	18–19	20
Brazil	20	176	985	25	17	21
World	2,034	13,164	85,987			

^a The USSR in 1990–1992

Fig. 2 Russia's place in the world scientific output: By various types of carbon nanostructures

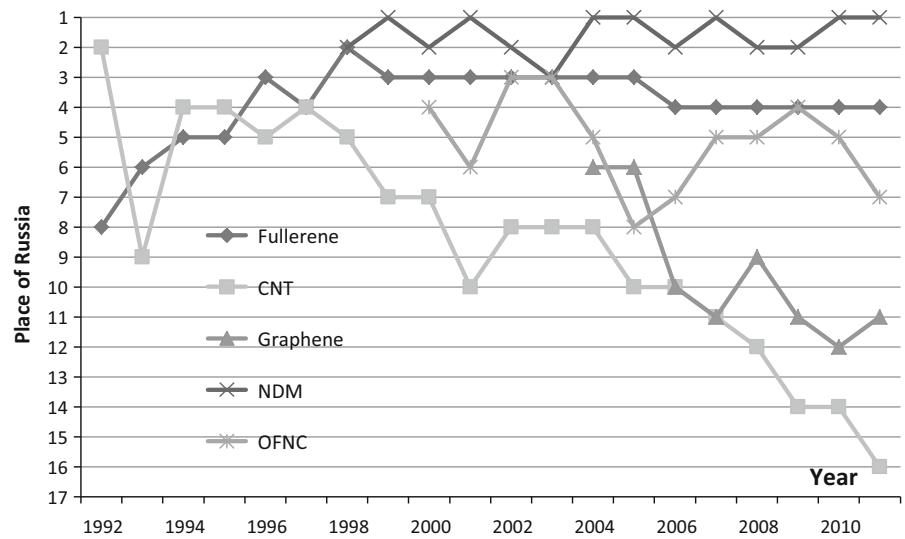
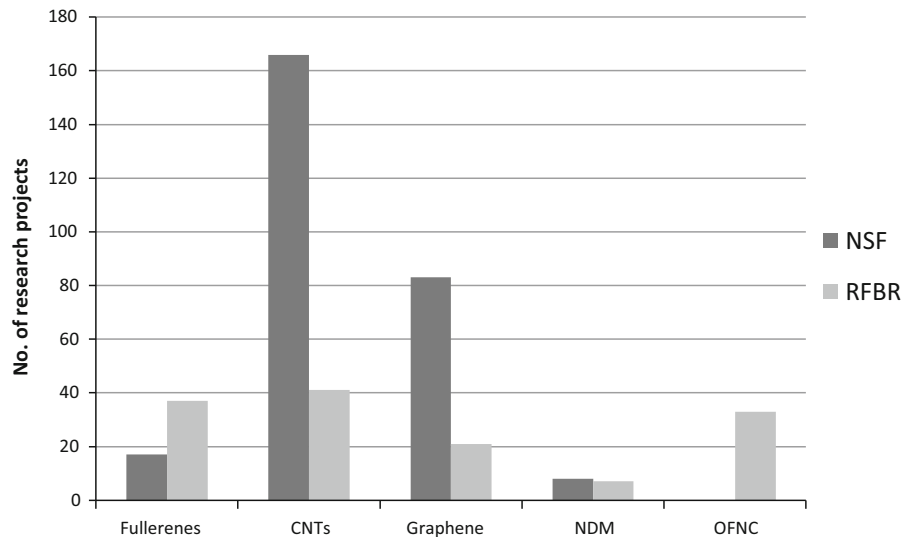


Fig. 3 Number of research projects by types of carbon nanostructures launched by the NSF and the RFBR during 2007–2011



countries with more than 100 C-nano publications each by the average number of citations per paper. By the first indicator, Russia only lags behind China in BRIC, while by the second indicator it also falls behind India and Brazil. Since the average number of citations varies significantly across subfields (from 15.2 times for NDM, up to 50.8 times for graphene), it would be more precise to compare citation performance at the level of countries using the “crown” indicator, that normalizes such differences. In Table 2, this indicator is calculated according to citation data obtained as at March 2014 (more than a year after the

principal collection of data). In terms of a more perfect measurement than average (and considering expanded citation interval), there has been a partial re-ordering of countries. Consequently, Russia has risen by three places, while Brazil has fallen. China and India, respectively, have risen by two places. Nonetheless, and on this indicator Russia remains in the last place in BRIC.

At this stage, let us turn to the most cited C-nano publications, namely 103 C-nano publications with >1000 citations. Some 61 of these publications deal with CNTs vs. 32 with graphene, 9 with fullerenes, and

Fig. 4 Cumulative citation of C-nano publications for 1990–2010: In total and by types

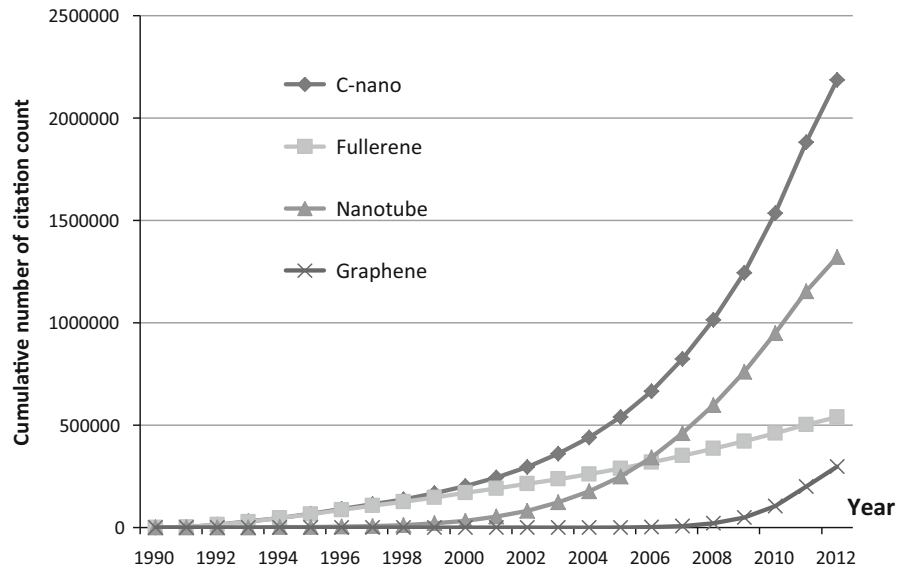


Table 2 Ranking countries by citation to C-nano publications

Rank	Country	Total citations to all C-nano publications for 1990–2010 years	Average citations per C-nano publication	“Crown” indicator	Rank countries according to average/”crown” indicators*
	World	2,189,207	30.1	–	–
1	USA	986,133	49.9	1.60	2/3
2	China	284,981	20.1	0.70	28/26
3	Japan	280,469	29.6	1.02	16/13
4	Germany	186,424	35.9	1.21	8/8
5	UK	169,623	46.6	1.62	4/2
6	France	122,719	34.0	1.14	9/10
7	South Korea	82,602	20.6	0.69	27/27
8	Netherlands	66,064	80.1	2.34	1/1
9	Russia	65,001	15.1	0.61	36/33
10	Italy	62,027	28.4	0.94	17/18
11	Spain	56,833	31.6	0.99	13/14
12	Switzerland	52,010	46.6	1.45	3/4
13	Canada	36,471	26.3	0.83	21/23
14	India	35,722	19.4	0.67	31/29
...
19	Brazil	26,722	33.0	0.97	12/15

* Among 46 countries with > 100 C-nano publications

one with OFCN. Seventeen countries have contributed to the Top 103 C-nano publications. The U.S. (77 publications) made the greatest contribution, followed by Japan (11 publications), the Netherlands (10), the

UK (9), Germany (6), and France (6). Russia, with four publications on graphene, occupies seventh place. It is followed by China and Brazil, with each having three publications on CNTs. Thus, by representation in the

Top 103 C-nano publications, Russia is first in BRIC. This is due in a large part to the articles co-authored by A.K. Geim and K.S. Novoselov (both received the 2010 Nobel Prize in physics “for groundbreaking experiments regarding the two-dimensional material graphene”).

Evaluating the quality of C-nano research and its participants

Russia’s contribution to C-nano research for the entire period consists of 4,735 publications in peer-reviewed journals. Table 3 lists the Top 10 journals by the number of C-nano publications. Six of the Top 10 are Russian journals with small values of Impact Factor (IF). Nonetheless, although Russian scientists are published en masse in the low-impact domestic journals, they have more than 150 C-nano publications in highly influential foreign journals (Table 4).

More accurate measure of the publication’s influence is citation counts. The citation distributions are severely right skewed. In our case, 16.6 % of Russian C-nano publications have not received any citations at all (Table 5), while 81.5 % of them have attracted few (lower than average) citations. Sixty one C-nano publications with >100 citations (or 1.4 % of all C-nano publications) have contributed to 44.4 % of total citations. In its entirety, the actual distribution in Table 5 corresponds to the “20/80 law,” according to which 20 % of all publications account for 80 % of the citations.

The group of 61 publications has two primary functions: offering a thematic analysis and identifying the highest quality Russian research in C-nano. Seventeen publications, receiving a total 20,875 citations, are devoted to graphene. Of these, 11 were written by scientists from IMT RAS in co-authorship with scientists from England and the Netherlands (the coauthors of two articles were scientists from the U.S. and Germany). All of the publications have appeared in prestigious journals, with the four most cited publications occupying 2nd, 5th, 41st, and 56th place in the world’s Top 103, respectively. Scientists from Landau Institute for Theoretical Physics (ITP) RAS and Saint Petersburg State University (SPbSU), along with foreign colleagues, are coauthors of six highly cited publications on graphene.

IMT RAS, additionally, has in the aforementioned 61-strong group two publications on CNTs. Moreover, the average number of citations per C-nano publication of this Institute is a record (501.9). According to this indicator, it surpasses the lead foreign organizations: the University of Manchester (185.5 citations on average), Stanford University (113.1), and IBM Corp. (103.5). Nonetheless, it significantly yields to them in its overall number of C-nano publications. Many of the 24 highly cited publications covering nanotubes reflect research on this subject implemented at Lomonosov Moscow State University (MSU), Prokhorov General Physics Institute of the RAS and IMT RAS, with respect to formation mechanism, isolation, purification, and CNT applications. There is also interest in non-carbon nanotubes in five publications.

Table 3 Top 10 journals with the greatest number of Russian C-nano publications

Rank	Journal	Country	IF-2011	No. of C-nano publications
1	Physics of the Solid State	Russia	0.711	298
2	Fullerenes Nanotubes and Carbon Nanostructures	USA	0.772	261
3	Russian Chemical Bulletin	Russia	0.379	245
4	Technical Physics Letters	Russia	0.565	177
5	Molecular Crystals and Liquid Crystals	England	0.580	176
6	Russian Journal of Physical Chemistry A	Russia	0.459	151
7	Physical Review B	USA	3.691	149
8	JETP Letters	Russia	1.352	136
9	Russian Journal of Applied Chemistry	Russia	0.283	111
10	Chemical Physics Letters	Netherlands	2.337	102

Table 4 C-nano publications from Russia in journals with high impact

Rank	Journal	Country	IF-2011	No. of C-nano publications
1	Nature	England	36.235	2
2	Nature Materials	England	32.841	1
3	Science	USA	31.201	10
4	Nature Nanotechnology	England	27.270	2
5	Nature Physics	England	18.967	3
6	Nano Letters	USA	13.198	14
7	ACS Nano	USA	11.421	7
8	Journal of the American Chemical Society	USA	9.907	21
9	Proceedings of the National Academy of Sciences of the United States of America	USA	9.681	1
10	Small	Germany	8.262	4
11	Nano Research	China	6.970	2
12	Carbon	USA	5.378	89

Table 5 Distribution of citations to Russian C-nano publications

No. of citations	No. of C-nano publications	Total no. of citations
0	712	0
1	550	550
2	448	896
3	370	1,110
4	282	1,128
5	195	975
6	195	1,170
7	148	1,036
8	142	1,136
9	99	891
10	88	880
11–20	525	7,713
21–30	215	5,414
31–40	115	3,957
41–50	56	2,558
51–60	34	1,861
61–70	33	2,148
71–80	18	1,362
81–90	9	761
91–100	6	580
>100	61	28,875
Total	4,301	65,001
Average		15.1
Median		4.5

Seventeen highly cited publications on fullerenes include works performed at the Nesmeyanov Institute of Organoelement Compounds (INEOS) RAS since the late 1960s, research work on superhard fullerite (the Research Center for Superhard Materials), on fluorinated C60 (MSU), and etc. Furthermore, RAS Institutes are represented in three highly cited publications on NDM. Apart from graphene, two more publications of year 2009 quickly got over a hundred citations. These are devoted to gold-plated CNTs for non-invasive targeted imaging of molecular structures in vivo, as well as new fullerene derivatives for bulk heterojunction solar cells. RAS scientists participated in both studies. Overall, they contributed to 80.3 % of Russian highly cited C-nano publications, thus becoming the leaders for this indicator. MSU, with 14.8 %, comes directly after the RAS.

The RAS's share in the total number of Russian C-nano publications for the studied period is 70.9 %; eight of its institutes are among the Top 10 for prolificacy (Table 6). Seven of the ten most productive Russian scientists in the C-nano field are also from the RAS. S.V. Morozov, from IMT RAS, has the record average citation index (Table 7). The foregoing confirms RAS's leading role at the sector level of organization for Russian science. However, over the

last three years (2009–2011), RAS's share was by about 4 % points lower than over the entire period, while HEIs share was by 10 % points higher. This is the result of a stimulated shift in the focus of research activity from RAS to universities. The latter, however, not yet accompanied by a change in the ratio of average citation of produced C-nano publications—4.9 times (RAS) versus 3.5 times (HEIs)—at the time of the study. Among world research organizations, RAS is number two after the Chinese Academy of Sciences: 3,357 versus 3,590 C nano publications for the period, respectively. The average number of citations per publication is likewise in favor of the Chinese Academy: 22.5 versus 15.2 times. In the world ranking of universities by the number of C-nano publications, MSU stands at 16th place. By this indicator, Tsinghua University (China) is leader with 1,386 C-nano publications, while the University of Manchester has the highest figure for the average number of citations per C-nano publication.

Patterns of research collaboration

Collaboration is an important feature of modern science. In bibliometrics, co-authorship is the most studied indicator of collaboration. Now we apply this

Table 6 Top 10 Russian institutions by the number of C-nano publications, 1990–2011

Rank	Institution/organizational structure	No. of C-nano publications	Average citations per C-nano publication	H-index
1	MSU	605	14.4	42
2	PTI RAS	534	8.7	30
3	IPCP RAS	353	8.9	26
4	INEOS RAS	259	8.7	20
5	ISSP RAS	228	6.9	21
6	IMC RAS	213	7.1	17
7	SPbSU	207	5.9	14
8	NIIC SB RAS	150	8.6	18
9	IS RAS	128	16.2	24
10	IBCP RAS	126	10.8	19
	RAS	3,357	15.2	–
	HEIs	1,621	9.1	–
	SRI & SRCs	475	10.3	–

PTI RAS Ioffe Physical-Technical Institute of the RAS, *IPCP RAS* Institute of Problems of Chemical Physics of the RAS, *ISSP RAS* Institute of Solid State Physics of the RAS; *IMC RAS* Institute of Macromolecular Compounds of the RAS, *SPbSU* Saint Petersburg State University, *NIIC SB RAS* Nikolaev Institute of Inorganic Chemistry of the Siberian Branch of the RAS, *IS RAS* Institute for Spectroscopy of the RAS, *IBCP RAS* Emanuel Institute of Biochemical Physics of the RAS, *HEIs* Higher Education Institutions, *SRI & SRCs* Sectoral Research Institutes and State Research Centers

Table 7 The most productive Russian scientists in the C-nano field, 1990–2011

Name of scientist	Institution	No. of C-nano publications	Average citations per C-nano publication	H-index
1. Boltalina OV	MSU	165	20.3	32
2. Lyubovskaya RN	IPCP RAS	130	13.7	22
3. Okotrub AV	NIIC SB RAS	109	8.0	15
4. Konarev DV	IPCP RAS	107	13.5	21
5. Sidorov LN	MSU	104	15.7	23
6. Chernozatonskii LA	IBCP RAS	103	14.3	21
7. Shulga YM	IPCP RAS	97	7.9	15
8. Zgonnik VN	IMC RAS	88	6.1	12
9. Bulusheva LG	NIIC SB RAS	84	8.1	14
10. Troyanov SI	MSU	80	13.4	19
Morozov SV	IMT RAS	23	875.2	19

Table 8 Authorship collaboration in C-nano publications; effect on the citation impact

No. of authors	No. and share (%) of publications						Average citation for publications of years 2005–2009 ^a
	1990–2011		1990–2000		2001–2011		
	No.	%	No.	%	No.	%	
1	296	6.3	87	6.8	209	6.1	7.5
2	679	14.3	170	13.3	509	14.7	8.5
3	794	16.8	218	17.0	576	16.7	8.1
4	758	16.0	246	19.2	512	14.8	6.6
5	650	13.7	179	14.0	471	13.6	7.8
6	525	11.1	145	11.3	380	11.0	7.2
7	389	8.2	98	7.7	291	8.4	19.3
8	246	5.2	57	4.5	189	5.5	13.8
9	152	3.2	38	3.0	114	3.3	24.6
≥10	246	5.2	41	3.2	205	5.9	26.5
In total	4,735	100.0	1,279	100.0	3,456	100.0	10.6

^a Three articles on graphene, having peak citations of 4,871, 1,621, and 1,389 times and with 8, 7 and 7 authors, respectively, were excluded from the calculations

measure in regard to Russian C-nano publications. Table 8 shows that 93.7 % of all Russian C-nano publications have multiple authors, among which three-author publications (16.8 %) have the largest share. According to Table 8, during 2001–2011 (vs. 1990–2000), a small redistribution took place favoring seven-or-more-author publications, with this happening at the expense of others (excepting two-author publications). As a result, the average number of authors per publication has grown from 4.5 in the initial period to 4.8 in the latter one. Since 2001, this

indicator has varied in the range of 4.5 to 5.0 on a yearly basis. For example, it equaled 4.7 in 2007 and 5.0 in 2011. By comparison, the average number of authors per Thomson-Reuters-indexed paper increased from 3.8 in 2007 to 4.5 in 2011 (King 2012). Consequently, according to this indicator, Russian scientific publications in the considered field are in the world trend, even with small excess.

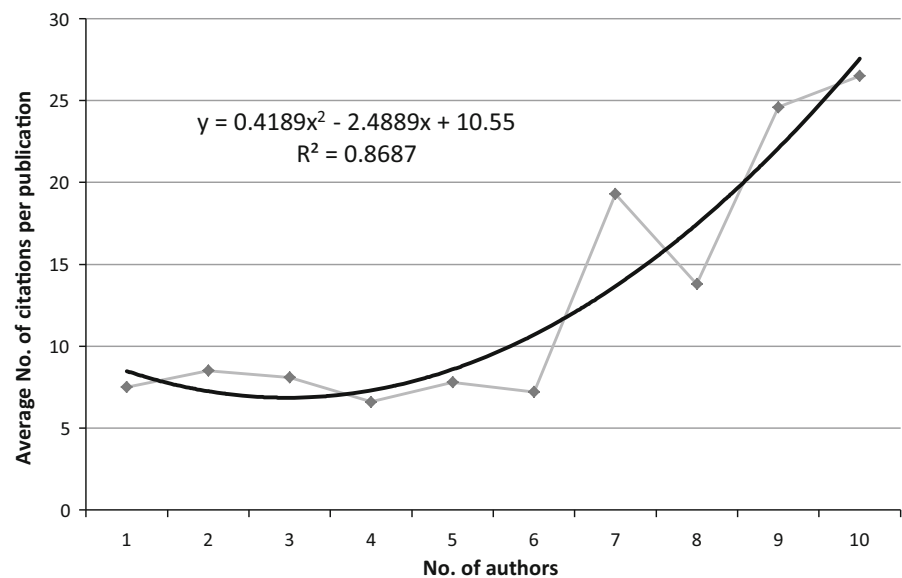
We have tried hereafter to use a more accurate CC indicator which makes the difference among levels of multiple authorships and is normalized. Russian

C-nano publications for the entire period, for instance, show that $CC \approx 0.697$ (0.691 for 1990–2000 and 0.700 for 2001–2011, respectively). This is higher than the coefficient values for all Indian nano publications in 1990–2009 (Karpagam et al. 2011). The prolific institutions and individual scientists, as a rule, have a CC that is above the average value. So, MSU has $CC \approx 0.760$, while for O.V. Boltalina $CC \approx 0.818$. In bibliometrics, collaborative publications have been linked with a more high citation impact (Katz and Martin 1997). For example, Costas and Bochove (2012) have used a logarithmic model to study the relationship between impact and the number of authors of papers. The polynomial in Fig. 5 fairly well approximates the data from Table 8 describing this relationship. According to this Figure, the average citation index increases significantly, beginning with seven-author publications. Interestingly, among seven-or-more-author publications, internationally co-authored publications begin to numerically dominate over publications with domestic co-authorship. Figure 6 shows the increment of citation impact due to international co-authorship in more detail. Overall, Russian C-nano publications with international co-authorship are cited on the average fourfold more than those written only by domestic scientists. This fact should force us to more closely mull the implications of international collaboration by Russian scientists in the C-nano field.

More intensive international research collaboration is typical for the nanotechnology development. So, the share of international co-authorship for all Russian publications in DB SCIE over the period 1990–2011 is 29 %, while those for all nano publications and C-nano publications is 41 and 36 %, respectively. In the C-nano field, Russia has collaborative links with more than 60 countries. The country's closest partners are Germany (collaboration covers 8.1 % of all Russian C-nano publications), the U.S. (7.0 %), England (4.8 %), France (3.5 %), and Japan (3.5 %). Russia's leading collaborator in fullerenes and graphene is Germany, while in CNTs and NDM it is the U.S. Historical ties between Russia and Ukraine continue to contribute to collaborative research: about 1.5 % of analyzed Russian C-nano publications are co-authored with Ukraine. Compare this with the collaborative research level between Russia and its economic peers in BRIC: only 0.9 % of publications are co-authored with Brazil, 0.7 % co-authored with China, and 0.2 % with India.

Collaborative research work provides the highest citation impact for publications on graphene co-authored with the Netherlands (292.3 citations on average per publication) and with England (116.7). Co-authorship with scientists from England (in fullerenes), from the U.S. (in CNTs), and from Japan (in NDM) is the most profitable in terms of the average citation. Figure 7 shows a rapid growth of the share of

Fig. 5 Relationship between author collaboration and citation impact: for 1,627 Russian C-nano publications for the period 2005–2009



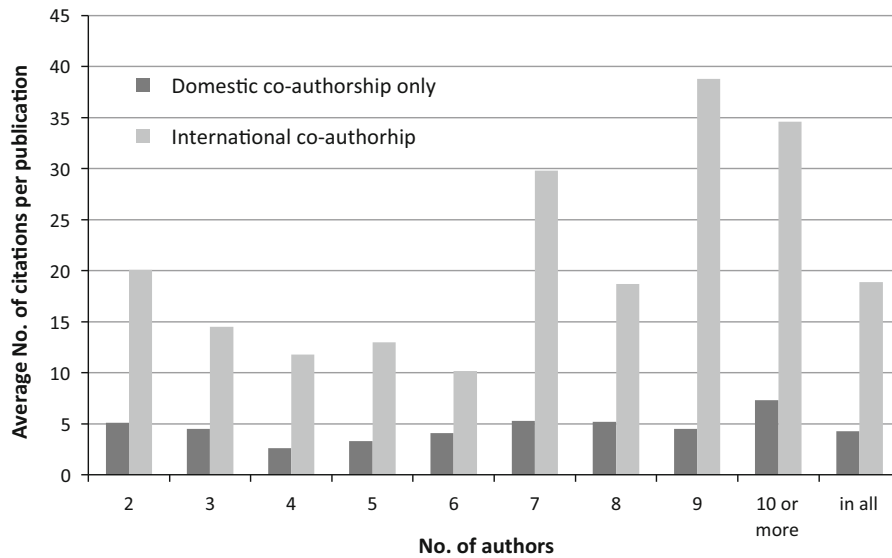
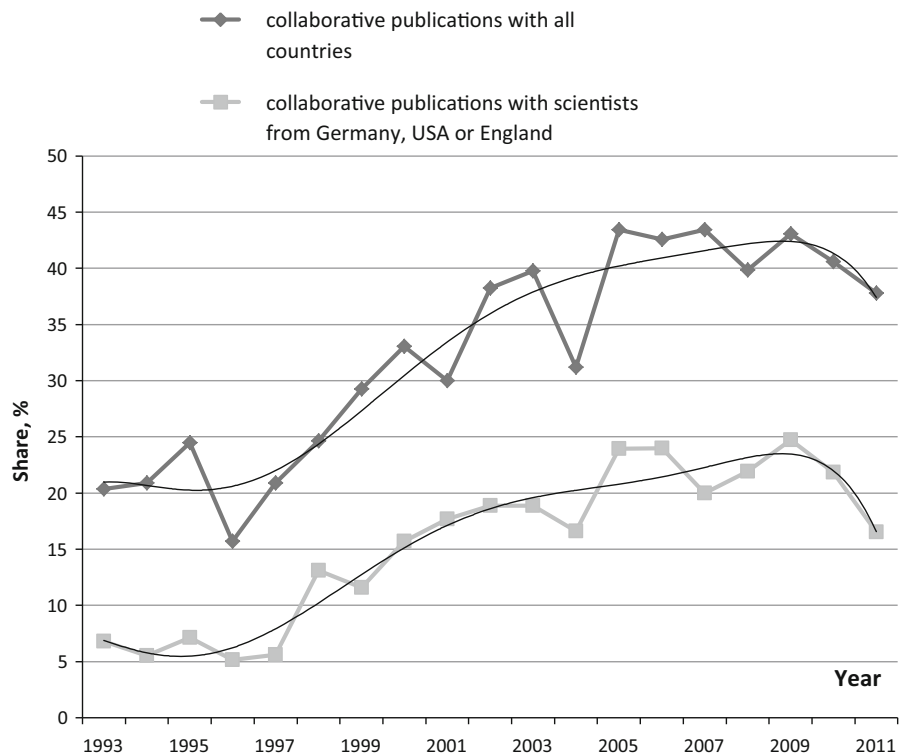


Fig. 6 Average effects of domestic and international co-authorship on the citation of C-nano publications

Fig. 7 Changing the share of Russian C-nano publications having international co-authorship



internationally collaborative Russian C-nano publications in 1996–2000, then a slower increase, and, finally, a sharp decrease at the end of the period under consideration. Such a decrease could be interpreted as

a negative sign due to two significant facts: the greater citation impact of publications with foreign coauthors; and the detail that 80.3 % of highly cited Russian C-nano publications are internationally co-authored.

Consider the pattern of international collaboration at meso-level using as an example the largest Russian university (MSU) and academic research institute (PTI RAS). During 2000–2011, share of international co-authorship in publications of these Russian leaders in C-nano amounted: 55.9 % from 487 publications and 40.9 % from 399 publications, respectively. MSU's international co-authorship links are more extensive and diverse due to two significant factors: the multi-disciplinary nature of C-nano research (in which the Faculties of Chemistry, Physics and Materials Science participate) and the specificity of the educational institution. There are a total of 30 countries participating in international collaborations with MSU, including Germany (which accounts for 24.6 % of MSU's C-nano publications), the U.S. (14.6 %), and England (9.7 %). PTI RAS, for its part, has collaborative links with scientists from 28 countries, including those from the U.S. (which accounts for 10.8 % of the PTI RAS C-nano publications), Germany (9.8 %), and Sweden (6.5 %). This Institute, at the same time, actively collaborates with scientists from the former Soviet republics: including Ukraine, Belarus, and Uzbekistan. MSU tends to collaborate with foreign universities, while PTI RAS, by comparison, tends to collaborate with foreign academic institutes (among others those located in Ukraine, Uzbekistan, Poland, and the Czech Republic).

MSU's major collaborators for 2000–2011 included Colorado State University (the U.S.), Humboldt University (Germany), and University of Sussex (England); these schools, respectively, participated in 48, 41, and 33 collaborative publications. MSU's Laboratory of Thermochemistry has conducted research of fullerenes and their derivatives, thereby making a significant contribution to the publication output and collaborative links with these schools. O.V. Boltalina, a representative of the Lab, is among the ten leading scientists in the C-nano field in the world. PTI RAS's primary collaborators for 2000–2011 included Umea University (Sweden), the Institute of Semiconductor Physics (National Academy of Sciences of Ukraine), and the U.S. DoE National Labs (Los Alamos, Oak Ridge and Livermore) with these organizations, respectively, taking part in 23, 12, and 10 collaborative publications. PTI RAS launched its collaboration with Umea University in the field of fullerenes when T.L. Makarova, a fellow of the Institute (Laboratory of the Cluster Structures

Physics), received a post-doctoral position at the Swedish University. Unfortunately, both scientists (O.V. Boltalina and T.L. Makarova), who had provided a very significant number of collaborative C-nano publications for MSU and PTI RAS, are no longer affiliated with Russian organizations. Instead they are working for Colorado State University and Umea University.

It is impossible to estimate the prospects of growth and quality of research in the C-nano field without, at least briefly, touching on the problems of scientific personnel. In the 1990s, Russia went through a transformation of the economic system, which profoundly affected the sphere of science. Its chronic underfunding led to a brain drain, with the best-qualified scientists of the most productive age emigrating. According to the Ministry of education and science of Russia, only between 1989 and 2004 around 25,000 scientists have left the country permanently and 30,000 on temporary contracts (RVC 2013). Among the main reasons for emigration there were low wages, poor material-technical and instrument base, low prestige of scientist status in Russia and constriction of the opportunities for scientific self-realization. As for C-nano, many active and talented scientists, in addition to Boltalina and Makarova, have emigrated from Russia and now continue their work in the West. These include

- A. K. Geim and K. S. Novoselov, graphene pioneers, who now work at the University of Manchester (England);
- A. P. Moravskii, who one of the first has reproduced in Russia the arc method of fullerene synthesis opened by W. Kratschmer in early 1990s. Now A. P. Moravskii works at the Materials and Electrochemical Research (MER) Corporation, Arizona (USA);
- O. A. Shenderova, among the world's top five scientists in NDM, who now works at the International Technology Center, North Carolina (USA).

When combined with internal mass outflow of qualified professionals from the field of R & D to other areas, which far from their education and work experience, the external brain drain has spawned a scientific generations' gap, destroying the normal process of transfer of scientific knowledge. This gap is also associated with a problem of aging Russian

scientists. For illustration, in 2011, the average age of the ten most productive Russian C-nano scientists (Table 7) was around 62 years. For the most part, owing to the generations gap, no adequate replacements for them exist. So, in 2011, the average age of the ten Russian C-nano scientists, which were the most productive during 2009–2011, was about 54 years. By this we add that in RAS and MSU, which produce the lion’s share of the Russian C-nano publications, the average age of researchers and faculty members in 2011 was equal to 51–53 years (Terekhov 2013). In this way, to compete at the forefront of nanoscience, Russia should prepare a new generation of researchers. But this could be a long and difficult process even under the best economic conditions.

C-nano patent analysis

Since patents focus on applied research, patenting statistics might say more about the potential economic impact of nanotechnology. Unfortunately, Russia has inherited from the USSR a weak tradition of patenting, especially on an international scale. Accordingly, at the time of adopting the Presidential initiative “Strategy of nanoindustry development” in 2007, the country’s share in international nanotechnology patents was less than 0.2 % (Government of the Russian Federation 2008). In fact, the OECD report

indicated that Russia’s share in the nanotechnology patents filed under PCT during 2004–2006 was only 0.39 % (OECD 2009). Of the BRIC countries, only Brazil with 0.21 % lagged behind Russia, while the shares of China and India were 1.01 and 0.51 %, respectively.

At this stage, we will try to clarify the patent statistics for Russia with respect to C-nano. The general trend (Fig. 8) suggests that C-nano innovation is on the rise around the world. So, the compound annual growth rate (CAGR) between 2000 and 2011 for USPTO-issued C-nano patents amounted to 31.2 %. This rate is higher than the rate of U.S. C-nano publications (17.4 %) and world-wide C-nano publications (19.7 %) in DB SCIE for the same period. For comparison, CAGR for C-nano patents issued by Rospatent between 2000 and 2011 was 17.6, versus 7.7 % for Russian C-nano publications in DB SCIE over the same period. This trend—a declining ratio of scientific publications versus patented inventions—indicates the emergence of more applied or commercially viable C-nano technologies.

Table 9 counts the C-nano patents granted (or filed for WIPO) for the entire period, based on the country of at least one inventor’s address. Data in the Table’s last column for the WIPO show that the contribution of each of the BRIC countries to the C-nano patents is greater than that to the nano patents in general. Chinese inventors contributed to 6.7 % of USPTO and

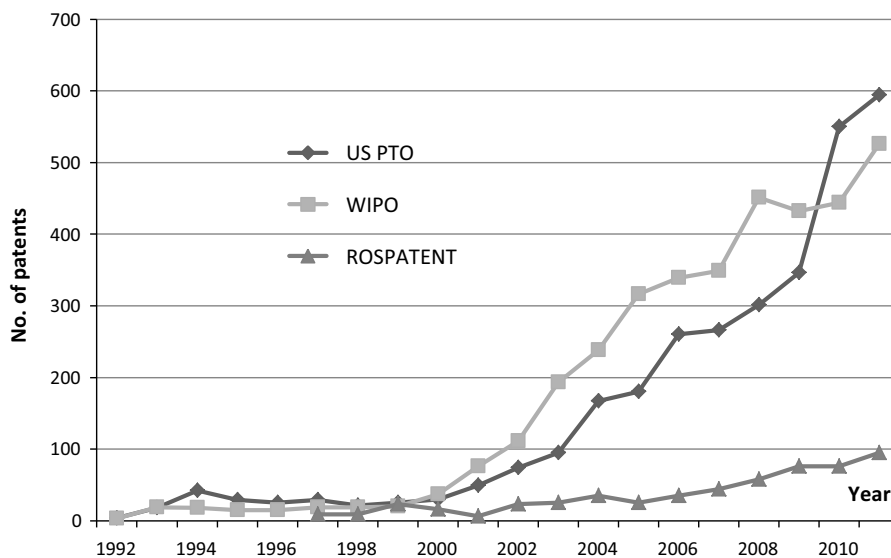


Fig. 8 The number of C-nano patents granted by the USPTO and Rospatent or filed under PCT in the WIPO from 1992 to 2011

Table 9 C-nano patents by country of the inventors: BRIC

BRIC countries	Patent organization (office)	Number (%) of patents by type of carbon nanostructures					
		Fullerene	Nanotube	Graphene	NDM	OFNC	Total
Brazil	WIPO (PCT)	0 (0)	8 (0.3)	1 (0.33)	0 (0)	0 (0)	9 (0.25)
	US PTO	0 (0)	2 (0.08)	0 (0)	0 (0)	1 (0.62)	3 (0.1)
Russia	WIPO (PCT)	24 (3.7)	8 (0.3)	4 (1.32)	5 (13.51)	6 (2.35)	47 (1.29)
	US PTO	8 (1.6)	1 (0.04)	0 (0)	3 (27.27)	4 (2.48)	16 (0.52)
	Rospatent	283 (97.53)	175 (89.14)	1 (100)	51 (100)	45 (97.98)	555 (95.14)
India	WIPO (PCT)	2 (0.31)	22 (0.83)	4 (1.32)	0 (0)	1 (0.39)	29 (0.8)
	US PTO	2 (0.4)	12 (0.48)	0 (0)	0 (0)	0 (0)	14 (0.45)
China	WIPO (PCT)	3 (0.46)	35 (1.31)	13 (4.29)	0 (0)	1 (0.39)	52 (1.43)
	US PTO	1 (0.2)	198 (7.88)	0 (0)	1 (9.09)	8 (4.97)	208 (6.7)

Table 10 The structure of owners of Russian C-nano patents

Type of patentee	Share of C-nano patents, granted by the Rospatent to different owners, %	
	1997–2007	2008–2011
RAS	34.8	28.2
Individual patentees	24.4	27.2
JSC, CJSC, Co. LTD	18.4	16.7
FSUE	13.2	10.2
HEIs	8.8	19.0
Foreign companies	4.4	5.9
Others	0.4	1.3

JSC Joint Stock Company, *CJSC* Closed Joint Stock Company, *FSUE* Federal State Unitary Enterprise

1.43 % of WIPO C-nano patents, respectively, that puts them on top in BRIC. Second place belongs to Russian inventors, who contributed to 0.52 and 1.29 % of the same patents, respectively. But they made the highest contribution to USPTO and WIPO patents for nanodiamonds and fullerenes, as well as to WIPO patents for OFNC (Table 9).

Russia's international patent activity in C-nano is greater in general than it is in the nanofield. However, its level is still not satisfactory. As noted by Volder et al. (2013), CNTs research and development are complementary to the rise of graphene, from here Russia's inability in CNTs includes double damages. Frequently, foreign companies become the owners of patents for inventions with participation of Russians. This refers to 7 of 16 USPTO C-nano patents and to 17 of 47 C-nano patents filed in WIPO. Clearly, this reduces the economic importance of patent activity. The leakage of patentable ideas, along with brain

drain, is causing a further deterioration in the country's innovative capacity.

We now turn to the set of 555 C-nano patents granted by Rospatent for 1997–2011. CAGR for them between 2007 and 2011 equals 21.2 %, while between 2000 and 2011 it equals 17.6 %. Along with the increase in the HEI share in C-nano patents (Table 10), this confirms the impact of a government policy that promotes patenting and supports prioritization of innovative activities by universities. Table 10 shows that individual patentees and foreign companies increased their contribution to Russian patents after 2007, whereas at the same time RAS and the Russian domestic corporate sector reduced it.

Nanotechnologies have potentially high financial revenues, therefore in countries with developed innovation system, representation of the private sphere among the nano patent owners is high enough, for example, about 76 % in Canada (Beaudry and

Schiffauerova 2011). In Russia, we see a different picture: about 75 % of C-nano patent ownership fell, in 2008–2011, on the share of federally funded institutions of RAS and universities, as well as individuals, which also are largely budget users. A poor legal literacy of researchers and administrative personnel in the area of IP protection, the outstanding issues of IP rights allocation, as well as lack of supportive innovation infrastructure hinder the introduction of IP to economic turnover. The relative number of registered agreements on use of IP, where research institutes or HEIs owned the rights is small; together with the state enterprises, their share was only 16.3 % of the total amount of agreements in 2011 (RVC 2013). This often leads it to pre-term termination of patents, as has occurred with our set of C-nano patents. As of April 2013, RAS had the largest share of discontinued patents (61.8 %), versus 36.1 % for individual patentees and 31.3 % for HEIs. Foreign companies had the minimal share of 6.9 %, versus 14.1 % for FSUE, and 24.7 % for JSC, CJSC, and Co. Ltd. We add that the impossibility to effectively commercialize the scientific results is another contributing factor for brain drain.

From the standpoint of commercialization, the corporate sector is of greatest interest. Using the

extracted patents and publications, we were able to identify around forty Russian companies, representing small- and medium-sized businesses in the C-nano field. The ten most active of these are listed in Table 11. Almost all are from ten companies that were founded by scientists; some of them (such as NeoTechProduct Ltd and Kintech Lab Ltd) are research spin-offs. Quite successful commercial venture is TISNCM, Federal State Institution (FSI). For their part, the FSUE patentees are predominantly former large Sectoral Research Institutes. So, FSUE All-Russian Scientific Research Institute of Aviation Materials (FSUE VIAM) owns six RF patents in the field of C-nano, while FSUE Lukin Scientific Research Institute of Physics Problems owns four RF patents and one WIPO patent, and FSUE Central Research Institute of Structural Materials “PROMETHEY” (FSUE PROMETHEY) owns three RF patents. These three FSUE units are acting as the National Nanotechnology Network’s Head Organizations for thematic directions: “composite nanomaterials,” “nanoelectronics,” and “structural nanomaterials”, respectively (Terekhov 2013). The most active RAS representative in the field is IPCP, which owns fourteen RF patents and three WIPO patents, and has published 353 C-nano publications. Its Carbon CHG

Table 11 Ten most active Russian small and medium-sized companies in the C-Nano field: patenting and publishing

Company	Specialization	Patents and publications			
		Rospatent	WIPO	USPTO	SCIE
FSI TISNCM (Troitsk)	Superhard fullerites (production and application)	5	–	1	62
CJSC ILIP (St Petersburg)	Fullerene-based materials	11	–	–	40
CJSC Astrin-Holding (St Petersburg)	Nanodispersible fulleroid materials	7	2	–	6
JSC Diamond Centre (St Petersburg)	Ultradispersed diamond	3	1	1	5
NanoTechCentre Ltd (Tambov)	Synthesis of carbon nanomaterial “Taunit”	5	–	–	–
NeoTechProduct Ltd (St Petersburg)	Fullerene products and technologies	4	1	–	–
SPE EST Ltd (Leningrad region)	Production of fullerene-containing black	1	2	–	–
JSC Fullerene-Center (Nizhny Novgorod region)	Production of fullerenes	2	–	–	1
CJSC Desco (Nizhny Novgorod region)	Medical use of amino acid derivatives of fullerene	4	–	–	–
Kintech Lab Ltd (Moscow)	Designing of new materials, including CNT-based	–	–	–	16

TISNCM Technological Institute of Superhard and New Carbon Materials (Former Research Center for Superhard Materials), *SPE EST Ltd* Scientific-Production Enterprise “Energy saving technologies” Ltd

Ltd (Chernogolovka) research spin-off has so far created the only Russian production of pure SWCNTs. Twenty-nine Russian C-nano patents (about 16 % of all corporate sector patents) were granted to foreign companies from the USA, Japan, Germany and France, such as IBM Corp. (USA), SONY Corp. (Japan), BASF SE (Germany), and ARKEMA (France). The aforementioned indicates Russia's prospects of entering a corresponding sector in the world nanotechnology market.

Russia is most likely to realize its C-nano economic potential in the fields of fullerenes, NDM, and OFNC. That this could be so, is confirmed, for example, by the thematic structure of patents (Table 9) or the production specialization of small- and medium-sized businesses (Table 11). Among the specific technologies already conducted are the following:

- synthesis of superhard fullerite for use of it as structural and semiconductor material in metal-working and electronics (FSI TISNCM: Patent Nos 2,127,225 RU; WO/1998/016465 WIPO; and 6,245,312 US) (here and below see Appendix B);
- creation of fullerene-oxygen-iodine laser for application in laser energetics and in medicine (Institute for Laser Physics, a.k.a. ILP, of FSUE Vavilov State Optical Institute: Patent Nos 2,181,224 RU; and WO/2001/099245 WIPO);
- application of fullerene-containing nematic liquid-crystal complex with fast electro-optical response and liquid-crystal device based on said complex (ILP and Samsung Electronics Co Ltd: Patent Nos 2,397,522 RU; and 7,482,043 US);
- use of polymer composites with fullerenes and CNT in structural elements of aviation and space engineering (FSUE VIAM: Patent No 2,223,988 RU);
- technology of obtaining the non-linear optical media for laser radiation limiters as well as switches and filters for new-generation optical systems (CJSC Astrin-Holding and ILP: Patent No 2,238,577 RU);
- use of polyhedral multi-layer carbon fulleroid nanostructures (CJSC Astrin-Holding invention: Patent Nos 2,196,731 RU; and WO/2003/093175 WIPO) in other inventions;
- use of antifriction composite material in various branches of industry (FSUE PROMETEI and CJSC Astrin-Holding: Patent No 2,237,685 RU);
- creation and use of composition for manufacturing building materials (CJSC Astrin-Holding: Patent No 2,233,254 RU);
- use of sealing composites in structural elements of aviation and space engineering (FSUE VIAM: Patent No 2,263,699 RU).

In recent years, there is a growing interest in the potential usage of nanodiamonds in composites, lubricants, and as drug delivery vehicles (Mochalin et al. 2012). Russia already has historical traditions in the production and use of this material; it also has patents (Table 9). For instance, JSC Diamond Centre has patented a NDM production method that is safe and reliable; it has the improved technical, economical, and ecological parameters and allows to organize a wide production (Patent Nos 2,348,580 RU; WO/2007/078210 WIPO; and 7,867,467 US). SKN Ltd, a Snezhinsk-based company, has patented a method and device for synthesizing and purifying NDMs (Patent Nos 2,452,686 RU; and WO/2008/143554 WIPO). FSUE Altai (Biysk city), Russian pioneer of NDM production in bulk quantities, owns four RF patents for its application in machine-building and chemical technology. Other RF patents cover practically all areas of the above-noted NDM applications.

However, a global trend of the 2000s is associated, primarily, with CNTs and graphene (Noorden 2011; Cientifica 2013). Some 20 years after their discovery, CNTs have yet to reach large-scale commercialization (Noorden 2011). For its part, graphene could bring faster economic returns due, inter alia, to the relative facility with which it could be produced and handled (Cientifica 2013). There are only a few MWCNT manufacturers in Russia, with the chief one located in Tambov (NanoTechCentre Ltd). Russia's only producer of pure SWCNTs, Carbon CHG Ltd, has the capacity, sufficient only to provide the research. Yet the country does not even contain one graphene manufacturer. Of course, Russia has saved the certain resources, not being a party to false starts in CNTs applications (Noorden 2011). However, the absence of a developed practical base and trained personnel may hinder it from joining the wave of transformative graphene-based innovations. In order to avoid this eventuality, closer interaction seems to be required between science, business, and government. In fact, Nobelist K.S. Novoselov discussed such a possibility

at a meeting held with A.B. Chubais, Rusnano CEO, during the Third Nanotechnology International Forum (Moscow in 2010). Russia is reportedly determined to reach such a decision in principle; meanwhile, an alliance of this sort was set up in Manchester in September 2013. In that alliance, one of the world's largest graphene manufacturers (American company Bluestone Global Tech Ltd) entered a collaborative research partnership to open its European base at the University of Manchester. Specifically, work has already begun on the National Graphene Institute with funding from the UK Government and European Regional Development Fund; it will provide a center for industry and University academics to work side by side on emerging graphene applications. University academics represent in excess of 100 scientists and engineers, working on graphene and other 2D materials. K.S. Novoselov and A.K. Geim are among these personnel (Begum 2013).

Discussion and conclusions

Bibliometrics and patent analysis are often used to understand the trajectories of emerging nanoscience, innovation paths in nanotechnology from scientific knowledge to application to commercialization. Modern information systems contain databases and tools for this function. The performed study was addressed to such important subfield of nanoscience and nanotechnology as C-nano, with the results suggesting several conclusions.

In terms of scientific publications, covered by DB SCIE, the world boom of C-nano continues through the explosive growth of research on CNTs and graphene. This is accompanied by conspicuous alterations in the participating countries' ranking. By 2011, Russia had fallen to tenth place, with this reflected in its C-nano thematic profile. Following is a configuration of thematic structure for Russian C-nano publications: 60.8 %—fullerenes, 26.3 %—CNTs, 6.3 %—graphene, 4.3 %—NDM, and 4.1 %—OFNC. By comparison, 57.4 % of the global output of C-nano publications thematically falls on CNTs, 28.2 % on fullerenes, 11.9 % on graphene, 3.4 % on OFNC, and 0.9 % on NDM. Thus, in the subfields of fullerenes, NDM and OFNC, Russia retains comparative advantages, while with CNTs and graphene (most needed by the world) it stands at a disadvantage. The Russian

scientific sector's case appears to reflect a lack of timely reaction to the early-2000s global shift in trends from fullerenes to CNTs. Nor did Russia deal with the shortage of adequately trained researchers to develop CNTs or redirect them to subsequent graphene-based activities (Terekhov 2013). In fact, Russia appears to have taken the opposite research direction in 2007–2011, prolonging “conservative” structure for publication production at the expense of more suitable projects.

Russian scientists have written not a little publications (especially in the graphene field) for prestigious international journals. Yet the bulk of their work has been published in Russian journals and then translated into English. Low visibility of such journals is a major cause behind the lack of international citations for Russia's C-nano publications. In general, international co-authorship increases the citation impact of publications (for Russian C-nano publications, those with international co-authorship attract in average four times more citations than those without it). At this stage, the article deals with the share of Russian C-nano publications having international co-authorship: 80 % in the group of 61 highly cited Russian C-nano publications. Russia collaborates most intensively with countries from the leading group: Germany, the U.S., England, Japan, and France. The most “advantageous” collaborations, in terms of citation for the analyzed period, were with England (in the fields of graphene and fullerenes), the U.S. (in CNTs), and Japan (in NDM). In this regard, the study reveals that international collaboration has decreased in recent years (Fig. 7), and this may have adverse consequences. The leading Russian research organizations, MSU and PTI RAS, have strong collaborative links in the C-nano field with Humboldt University, Colorado State University, the University of Sussex, and Umea University. But two scientists actively involved in these links, (O.V. Boltalina and T.L. Makarova), have emigrated, and this fact will likely reduce the Russian “harvest” of thematic publications.

Presently, RAS is the chief organization-participant conducting C-nano research in Russia in both the number and quality of publications. Its institutes and researchers lead in the domestic rankings according to various bibliometric indicators. However, its situation with respect to foreign comparisons is not so commendable. The Chinese Academy of Sciences has produced more C-nano publications than RAS for the

period under consideration, receiving a greater number of citations per publication than its Russian counterpart. For their part, such institutes as PTI RAS and IMT RAS are relatively competitive internationally in C-nano research. MSU, the HEIs leader, trains specialists; it is 16th among world universities for the number of C-nano publications it has produced.

Three major patent databases indicate that patent activity is growing, exceeding the recorded growth rate in 2000s of scientific literature in C-nano field. This reflects, *inter alia*, the emergence in C-nano of more applied technologies, and the current desire to achieve C-nano's practical potential by the adoption of national nanotechnology programs. One of these, the "Strategy of nanoindustry development," has spurred C-nano patent activity in Russia from 2007.

However, the lifetime of Russian patents is often short since they enjoy few opportunities to be commercialized, especially from the side of budgetary organizations.

Really, a small group of large businesses is dominated in Russian economy that demonstrates comparatively little interest in innovation. So, in 2009, the share of industrial companies employing technological innovations, constituted only 9.4 % of the total number (RVC 2013). On the other hand, the main owners of patented inventions—research institutes and universities—do not have the necessary innovation infrastructure or favorable opportunities to enter the market of IP. To reanimate such a disjointed innovation system, the government has undertaken several initiatives. These included the following: creation of development institutions such as Russian Venture Company or JSC Rusnano; standardizing the creation of start-up and spin-off companies founded by the universities and research institutes to commercialize their IP; tax stimulation for innovation, *inter alia*, via a flexible taxation of intangible assets of companies, etc. Nonetheless, these efforts have yet to enjoy real success. Meantime, for example, Rusnano—number four in Fast Company⁴ ranking most innovative companies in Russia in 2011—could not even organize proper monitoring of the presence and use of IP objects in its project companies, than demonstrated unimportance of this aspect (Terekhov 2013). Or in

our case, despite the efforts of the government, only 7 % of all C-nano patents granted by Rospatent to universities and RAS in 2008–2011 were co-granted to them and businesses.

It would be worth for Russian businesses to strengthen its activities in international patenting, bearing in mind the long-term objective of attaining foreign markets. Whether it is done, domestic inventors unlikely will choose foreign companies as partners (such a move might eventually concede to them the right of patent owner). It should also be noted that leakage of patentable ideas might undermine Russia's competitiveness in global high-tech markets in the future.

The study's findings show that thematic directionality of Russia's research activity in the C-nano field has definitely affected the nature of its applied developments. The primary goal of the country's C-nano activities—with fullerenes, NDM and OFNC—is to contribute to the national economic development. Consequently, the thematic structure of its patents, the specialization of its small- and medium-sized businesses and the activities of its FSUEs are directed to this end. At the same time, Russian companies currently lack significant graphene- and CNT-related patent technologies, which could promote their commercial practice.

Russia leads the other BRIC nations by the number of the most cited C-nano publications (all devoted to graphene) and by the number of its USPTO and WIPO patents devoted to fullerenes and NDM. Only China leads Russia in terms of its total number of C-nano publications and citations received, as well as by the number of C-nano patents of USPTO and WIPO. Finally, Russia is last in BRIC according to two indicators: its average number of citations per C-nano publication, and its "crown" indicator. It might be worth noting here that the members of BRIC have a rather low level of internal collaboration in studied field.

Socio-economic crisis of the 1990s led to a wide-scale brain drain from Russia, devastating many science-technology fields and destroying the essence of many groundbreaking activities. The C-nano field has undergone this fate. Significant impediment for resolving this problem is demographic factor. Indeed, the anticipated replenishment youth in science will come from university graduates. But their numbers have decreased or become weaker due to the country's

⁴ Fast Company is the world's leading business media brand, specializing in the topic of innovation in technology, ethical economics, leadership, and design.

falling birth rate in the 1990s and downgrade of educational standards. When combined with the existing gap of scientific generations, this may become a long-term barrier for successful development of priority research fields in Russia. These problems have already been partly understood and accounted for in government policy. We mention only an ample funding the development of university science support of young talented scientists and use of the international brain circulation via contests of mega-grants for creation of world-class labs in universities. However, as in the case of progressive measures in the field of IP, the results of this policy are less certain.

Furthermore, it appears that Russian science may be afflicted by ill-informed policy decisions. In our opinion, assertive shift of the focus of research

activities from RAS to the weaker sector of higher education (beginning from 2006) will reduce the country's research performance. As a consequence, Russia may continue to lose ground on the global stage even in such successful fields as C-nano. Based on this case study, we believe an alternative strategy should be pursued, which bets on the integration of academic and university science, perfects the institute of IP to advance science-intensive industries, and promotes patents for innovations development.

Appendix A

See Table 12.

Table 12 List of keywords selected in the DB SCIE for search in C-nano field

No	Individual keywords and search terms	Frequency of occurrence in the titles of publications
1	Fulleren*	12,768
2	Metallofulleren*	511
3	Fullerid*	484
4	Buckminsterfulleren*	452
5	Fullerit*	429
6	Fullero*	328
7	Buckybal*	227
8	Azafulleren*	50
9	Endofulleren*	32
10	Fluorofulleren*	32
11	Dimetallofulleren*	30
12	C60 or C-60	11,531
13	C70 or C-70	1,595
14	Nanotub*	47,665
15	Buckytub*	44
16	Tubelene*	8
17	MWNT* or MWCNT*	1,032
18	SWNT* or SWCNT*	861
19	Peapod*	188
20	Graphen*	10,245
21	Graphan*	80
22	Nanodiamond*	803
23	(Carbon* and nanofiber*)	1,844
24	“Nanopor* carbon*”	322
25	Nanocarbon*	254
26	(Carbon* and onion*)	238
27	“Carbon* nanohorn*”	224

* Truncation of the term

Appendix B

See Table 13.

Table 13 List of patent documents mentioned in the article

Patent number	Title	Publication year	Patent owners (Applicants)
2,127,225 RU	Superhard carbon material, method of its production, and article made from superhard carbon material	1999	Individual patentees (from FSI TISNCM)
2,181,224 RU	Method for generating stimulated radiation across iodine atoms	2002	Institute for Laser Physics (ILP)
2,196,731 RU	Layered fulleroid-type polyhedral carbon nanostructures	2003	CJSC Astrin-Holding
2,223,988 RU	Polymer binder, composition material based thereon, and a method for preparation thereof	2004	FSUE VIAM
2,233,254 RU	Composition for manufacturing of building materials	2004	CJSC Astrin-Holding
2,237,685 RU	Antifriction composition material	2004	FSUE PROMETHEY; CJSC Astrin-Holding
2,238,577 RU	Non-linear optical element for limiting electromagnetic radiation flows	2004	CJSC Astrin-Holding; ILP
2,263,699 RU	Method of production of sealing composition	2005	FSUE VIAM
2,348,580 RU	Nanodiamond and method of its obtainment	2009	JSC Diamond Centre
2,397,522 RU	Fullerene-containing nematic liquid–crystal complex with fast electro-optical response and liquid–crystal device based on said complex	2010	N. Kamanina (from ILP); SAMSUNG ELECTRONICS CO LTD (KR)
2,452,686 RU	Apparatus for purifying and modifying nanodiamonds	2012	SKN Ltd (RU)
WO/1998/016465	A superhard carbon material, a method for its production, and articles made therefrom	1998	Individual patentees (from FSI TISNCM)
WO/2001/099245	Method and device for lasing a stimulated emission using iodine atoms	2001	Individual patentees (from ILP)
WO/2003/093175	Polyhedral multi-layer carbon fulleroid nanostructures	2003	CJSC Astrin-Holding
WO/2007/078210	Nanodiamond and a method for the production thereof	2007	JSC Diamond Centre
WO/2008/143554	Nanodiamond material, method and device for purifying and modifying a nanodiamond	2008	SKN Ltd (RU)
6,245,312 US	Superhard carbon material, a method for its production, and articles made therefrom	2001	FSI TISNCM
7,482,043 US	Fullerene-doped nematic liquid–crystal complex with high-speed electrooptic response and liquid–crystal device based on it	2009	N. Kamanina (from ILP); SAMSUNG ELECTRONICS CO LTD (KR)
7,867,467 US	Nanodiamond and a method for the production thereof	2011	JSC Diamond Centre

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