Developing nano research in Russia: a bibliometric evaluation

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Nanotechnology has attracted substantial global research, funding, and policy directives in recent years. The Russian government considers development of nanotechnology as a strategic goal to shift the economy in an innovative way, and in the medium term aims to make the country one of the world's leaders in nanotechnology. The question is, whether this is feasible. Since nanotechnology is largely science-driven, we focus in this article on the evaluation of the scientific performance in Russia and other countries in the field. Based on the Science Citation Index (SCI)-expanded web version, Russia has lost its competitiveness in terms of scientific performance. Its relative decline in percentage share of nanotechnology publications since 1997 is due to prolonged underfunding of science and the brain drain, as well as the competitive advances of other countries ahead of Russia in prioritizing nanotechnology at state level. Russia is thirteenth in the world in terms of the total number of citations to all its nanotechnology publications for the interval 1990–2008 and is in the fourth ten countries according to the average number of citations per publication. Russia is in the top ten countries by the number of high-impact publications thanks to domestic researchers in the field of graphene and bulk nanostructured materials. It has fairly good prospects in nanophotonics, as evidenced by bibliometric indicators and the availability of training opportunities for young researchers.

Keywords: bibliometric evaluation, carbon nanostructures, nanophotonics, nanotechnology

Introduction

Along with other convergent (bio-, info-, cogno-) technologies, nanotechnology promises to become a basis for the formation of the sixth technological order according to the classification of Russian economists D.S. Lvov and S.Y. Glazyev. Due to the specific features (science

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intensity, interdisciplinarity, multiple applications, etc.), the volume of resources invested and the scale of results expected it significantly interests scientists of different specializations, including science theoreticians, economists and experts in the fields of forecasting and management.

Understanding the development of nanotechnology (NT) is closely connected with the possibility of its measurement but official statistics, not having developed so far a satisfactory system of classification, do not quite cope with this task. That is one reason why bibliometric studies are so widespread.[1] NT development in Russia has its own history, where it is possible to identify:

- Initial exploration (until the 1980s);
- Technological emergence (1980s to the present time);
- Formation of mechanisms to support research under market conditions (1990s);
- State policy activation and acceptance of the presidential initiative "Strategy for development of nano-industry" (2000s).

If the first two stages are of interest mainly for historians of science, the following two are of interest for scientometric analysis and research evaluation. Indeed, to understand the processes of NT development adequately, to identify positions and possibilities of different countries in the global nanotechnology race and correctly to develop strategy, bibliometric analysis using authoritative international scientific databases is necessary. Such studies are carried out in Russia,[2] but they are still not enough. This study, part of a federal programme funded through the Russian Academy of Sciences (RAS), is continuing. We not only count papers and use the average impact of all papers published by some unit to be evaluated, but also use indicators reflecting the top citation distribution (such as highly cited articles).

First, we give some general bibliometric assessments of nanotechnology development in Russia in comparison with other countries, and then further dwell on such areas as carbon nanostructures and nanophotonics. Initial statistics were obtained from the Science Citation Index (SCI)-expanded database (Institute of Scientific Information (ISI) Web of Knowledge platform).

Some general indicators

To obtain initial statistics for the present study, we searched in the SCI-expanded database by keywords contained in the titles of publications. Along with words with a "nano" prefix, we included the following search terms: "fullerene", "quantum dot", "dendrimer", "photonic crystal", etc. Terms such as "nanogram", "nanosecond", "nanolitre" etc. were considered not relevant and have been excluded. This is an accepted search strategy to achieve the elimination of irrelevant and low-relevance works.

This approach identified 303,484 publications on the theme (nano publications) during the period 1990–2009, with authors or co-authors representing more than 120 countries. Figure 1 shows the leading ten countries according to their relative contributions to the world output of nano publications.

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[1] C. Huang et al., "Nanoscience and technology publications and patents: A review of social science studies and search strategies". *Journal of Technology Transfer* **36** (2011) 145–172.

[2] V.A. Markusova et al., "A bibliometric study of Russian R&D in nanotechnology". In: *Proceedings of the 12th International Conference on Scientometrics and Informetrics (ISSI'09), Vol. 1*. Rio de Janeiro, Brazil: International Society for Scientometrics and Informetrics (2009).

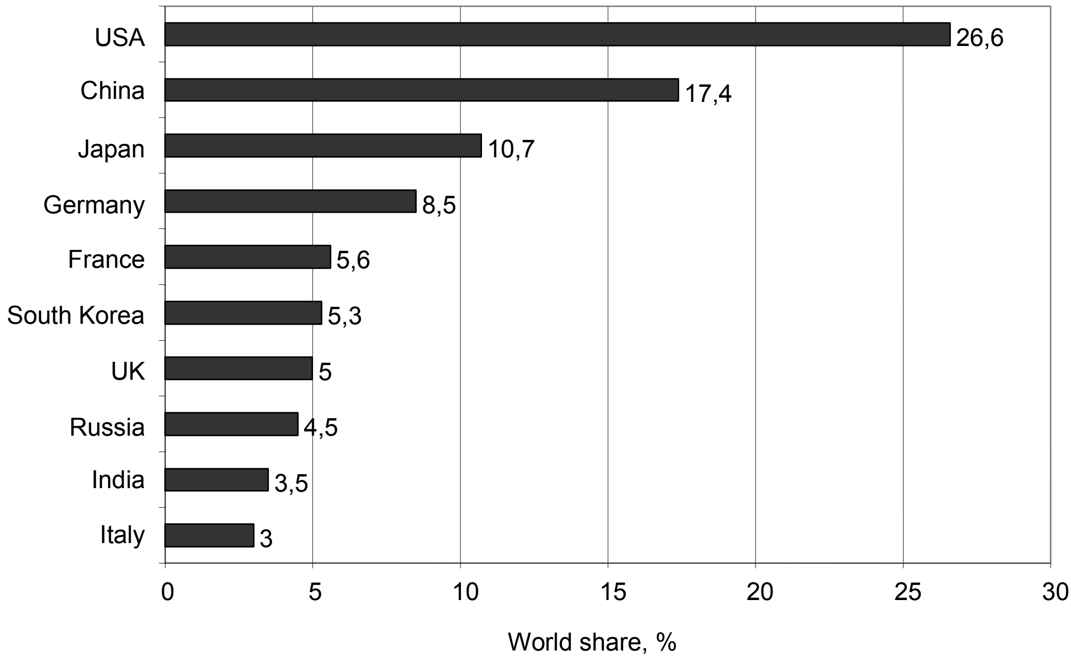

Figure 1. Percentage shares of world nano publications held by leading countries, 1990–2009.

Despite the increasing interest of domestic scientists in this field, Russia's contribution to the world output of nano publications over time is quite varied (Figure 2). Having reached a maximum of 8.1% (1997), it began to reduce steadily down to 3.5% (2009). As a result, the country has moved from 5th to 10th place by this indicator. Whereas in 1997 12 Russians were among the 100 most productive authors in the field of NT, in 2009 there were no Russians among the top 500 scientists. This negative tendency was a consequence of insufficient attention to science and poor target support of priority research areas in our country against the background of the adoption by many countries in the early 2000s of national programmes for NT development. Even the significant growth of financing in connexion with the adoption in 2007 of the presidential initiative "Strategy for development of nano-industry" could not reverse the situation. According to the number of nano publications, India and Taiwan, which in 1997 occupied the 14th and 15th places respectively, have already left our country behind in 2009. Unfortunately, a significant cause of the laggardness in Russia is a deep crisis among national research staff.[3]

For the evaluation of scientific performance and the formation of research policy, citation analysis is an important tool. In Table 1, calculated in October 2010, the countries are located in descending order of the total number of citations to all nano publications, produced by the given country during the interval 1990–2008. By this indicator Russia is thirteenth in the world. The

3 A.I. Terekhov, "Providing personnel for priority research fields (the example of nanotechnologies)". *Herald of the Russian Academy of Sciences* **81** (2011) 19–24.

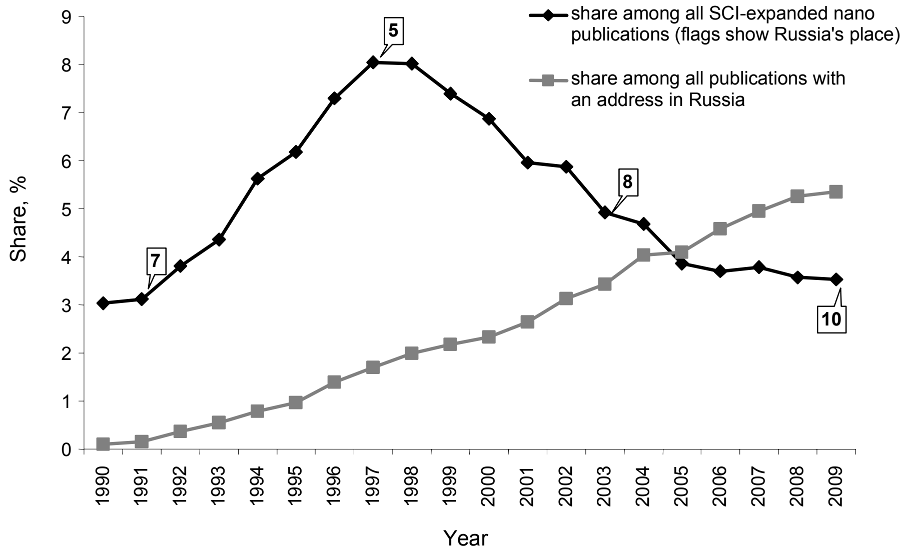

Figure 2. Percentage share of nano publications having an address in Russia among all Russian publications and among all SCI-expanded nano publications, year by year.

USA is the strongest nation in terms of scientific performance; it has the biggest contribution to the world output of nano publications. Although according to the average number of citations per nano publication the USA ranks third (after the Netherlands and Switzerland), they surpass the rest of the world according to the total number of citations to all their nano publications.

Table 1. Average numbers of citations according to publications by NT field and country.[a]

	Total number of nano publications, 1990–2008	"Nano" in general	Fullerenes	Nanotubes	Graphene	Nanophotonics
World	258,701	n.a.[b]	22.2	29.0	42.3	20.5
USA	72,949	31.3	42.7	47.6	56.7	32.4
Japan	29,413	18.8	20.7	31.3	18.3	24.1
China	42,848	12.8	8.0	17.8	20.0	8.2
Germany	22,747	23.1	27.4	33.2	48.9	23.4
UK	13,585	24.3	34.1	35.1	133.2	37.2
France	15,033	21.6	18.9	38.7	61.9	20.3
South Korea	12,953	13.8	14.6	17.4	15.7	14.5
Italy	7,860	18.6	26.1	24.5	16.3	15.1
Switzerland	4,230	32.8	33.8	54.0	47.9	22.1
Spain	6,470	19.3	23.0	26.8	39.1	24.5
Canada	6,125	20.4	21.9	17.6	30.0	23.2
Netherlands	3,582	33.7	40.1	86.1	107.5	34.7
Russia	12,091	9.9	7.3	13.1	131.1	14.3

[a] Calculated from the SCI-expanded database.
[b] Cannot be calculated because the number of processed documents is too large.

Bibliometric analysis of highly cited authors is of interest, but also high-impact publications. We found 140 nano publications that have each been cited a thousand or more times. Scientists from 15 countries are authors or co-authors of these publications. The greatest contribution (103 publications) belongs to scientists from the USA. They are followed by scientists from the UK (10), Netherlands and France (8 each), Japan and Germany (7), Switzerland and China (4), Russia and Italy (3). Articles devoted to the discovery of carbon nanotubes (CNT) (Japan; cited 9864 times), fullerenes (USA and UK; cited 6930 times) and a method for the fabrication of a silicon quantum wire array (UK; cited 5386 times) take the top rankings. Papers devoted to carbon nanotubes (CNT), with a share of 27%, dominate among high impact nano publications, followed by papers devoted to semiconductor nanostructures (17%) and then nanobiotechnology and nanomedicine (12%). This reflects the main research interests of the global nanotechnology community over the considered interval. In recent years, graphene has taken a clear priority, and suffice it to say that since 2005, three out of ten highly cited publications in the field of NT are devoted to it.

We found also 122 nanotechnology publications with an address in Russia that have been cited a hundred or more times. Two articles on graphene published by Russian scientists (at the Institute of Microelectronics Technology and High Purity Materials (IMT RAS)), one jointly with scientists from the UK in the journal *Science* (2004) and one jointly with scientists from the UK and the Netherlands in the journal *Nature* (2005), take up the 9th and 23rd places respectively in the global sample. For comparison, a review written by scientists from the Ufa State Aviation Technical University on the creation of bulk nanostructured materials using severe plastic deformation, published in 2000, ranks 38th in the same sample. 41% of these publications are devoted to semiconductor nanostructures, 25% to carbon nanostructures, 11% to nanophotonics and 7% to nanobiotechnology and nanomedicine. These parameters reflect the thematic structure of a significant Russian contribution to NT development. The share of publications with foreign co-authorship in the sample (87%) is much higher than among all Russian nano publications (43%); co-authorship with scientists from Germany, the USA and the UK are favoured the most. 80% of the publications from this sample have authorship from the RAS and 18% from higher education institutes. The leader is the Ioffe Physical-Technical Institute (PTI RAS) (36%), followed by the ITM RAS (12%) and the Lomonosov Moscow State University (MSU) (10%). Over half of Russian nano publications from 2005 with a hundred or more citations are devoted to graphene. Such seemingly disproportionate attention to graphene is due to cooperation (and co-authorship) with our former compatriots A.K. Geim and K.S. Novoselov, who in 2010 received the Nobel Prize for physics "for groundbreaking experiments regarding the two-dimensional material graphene".

This second Nobel Prize for a nanomaterial (the first having been in chemistry in 1996 "for the discovery of fullerenes") indicates the special role of carbon nanostructures for NT. In the opinion of well-known Japanese scientists, "if it were not for the discoveries of C_{60} in 1985 and carbon nanotubes in 1991, the coming of nanotechnology might have been delayed by at least a few decades".[4] The influence of these discoveries appears to be so great that articles on the

[4] M. Ozawa and E. Osawa, "Carbon blacks as the source materials for carbon nanotechnology". In: *Carbon Nanotechnology: Recent Developments in Chemistry, Physics, Materials Science and Device Applications,* pp. 127–151. Amsterdam: Elsevier (2006).

subject[5] remain the most highly cited among all publications on the theme. Having started 25 years ago, the race in the field of carbon nanostructures now holds the global research community in an intense search that is confirmed by the bibliometric analysis.

Carbon nanotechnology race

The discovery of fullerenes in 1985 by scientists from the UK and the USA initiated the beginning of the race. In 1990 a simple way to obtain fullerenes was found, and in three years the number of publications (articles, reviews, proceedings, letters) on the study of fullerenes and their derivatives exceeded one thousand per year in the world (Figure 3). Such a high interest in these compounds is due to the unusual properties of fullerenes, opening numerous opportunities for applications. The global fullerene boom predicated the discovery of carbon nanotubes: multi-wall in 1991 and single-wall in 1993. Surpassing the fullerenes in the unique properties and potential applications, CNT immediately attracted wide research interest. By 1992, the world having learned how to produce CNT in gram quantities, the global flow of publications devoted to them began to grow exponentially. In 2002 it exceeded the global flow of publications about fullerenes (Figure 3).

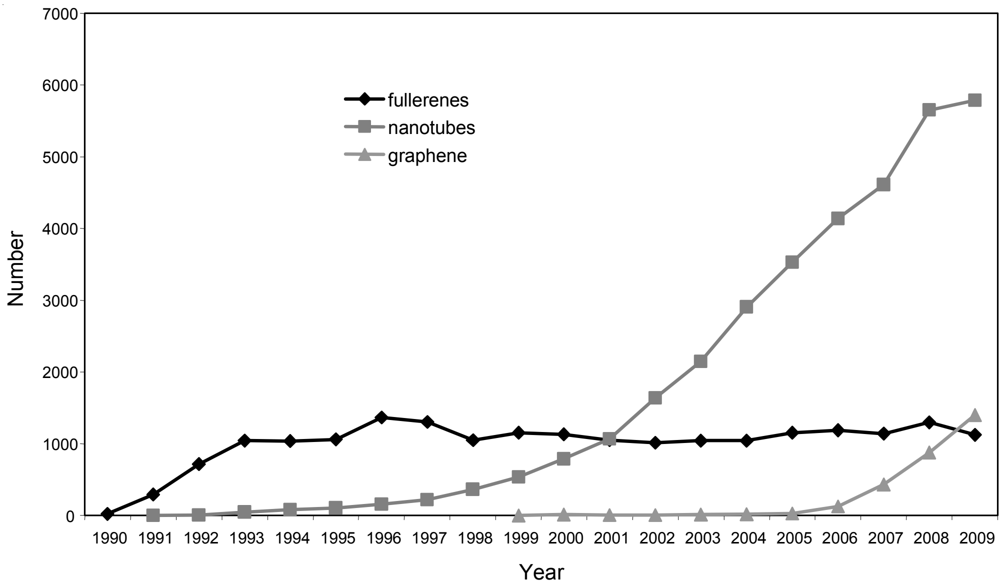

Figure 3. Number of publications dealing with carbon nanostructures, year by year.

The next growth point in the study of new forms of carbon was the experimental discovery of graphene in 2004[6]—a two-dimensional material with a thickness of one atom of carbon—a possible future basis of nanoelectronics (Figure 3). Explosive interest in this nanomaterial, even

[5] H.W. Kroto et al., "C-60—Buckminsterfullerene". *Nature* (Lond.) **318** (1985) 162–163; S. Iijima, "Helical microtubules of graphitic carbon". *Nature* (Lond.) **354** (1991) 56–58.

[6] K.S. Novoselov et al., "Electric field effect in atomically thin carbon films". *Science* **306** (2004) 666–669.

against the background of its two outstanding predecessors, is further demonstrated by Figure 4. More than 90 countries have participated in studying carbon nanostructures. Such industrially advanced countries as the USA, Japan, Germany, the UK, France, Italy, Spain and also Asian "tigers" (South Korea, Taiwan, Singapore) are or were in different years in the top ten by the number of publications. Developing giants—China and India—also have impressive results. China is among the top three in all three types of carbon nanostructures, and since 2007 it takes first place by the number of publications in the field of CNT. Scientists from South Korea published the first works on CNT in 1997; however, already in 2001 they were ahead of Germany and took the fourth place in the world. Over the same period, Taiwan has made significant progress, reaching 7th place in 2008. India has moved from the second ten countries to the top ten. Iran's sharp jump from 18th place in 2007 to 9th place in 2009 is amazing. Singapore was also quick to join in research on graphene. By the number of publications in the field of fullerenes and CNT, Japan almost never left the top three, and in the field of graphene it takes 4th place. Asian countries have relied on significant research activity in the field of carbon nanostructures. However, despite the powerful "Asian billow" of publications in this field, the average indicators of their influence according to the SCI-expanded database are not so impressive, except for the publications of Japanese scientists on CNT (Table 1). The elite collection consists of publications of scientists from the USA and some European countries. The USA has yielded first place in the field of fullerenes for short intervals, likewise Japan in CNT; China is the leader of this carbon nanotechnology race. American scientists first moved the focus from the study of fullerenes to the study of nanotubes: in 2000, for the first time the ratio of publications produced by them shifted in favour of nanotubes. By 2003 China was rushing in pursuit of the USA. These two countries are the most active in the study of graphene.

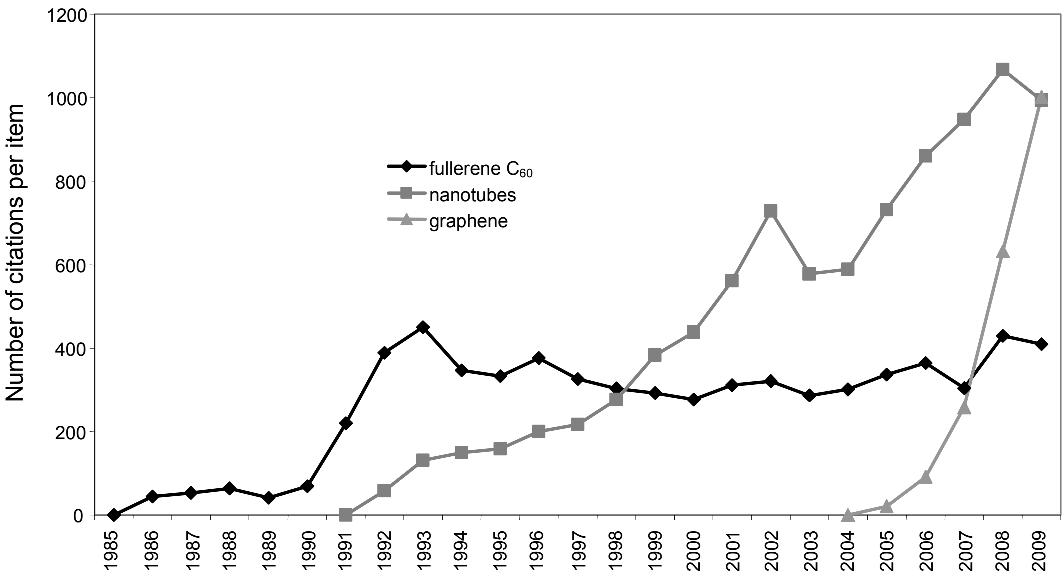

Figure 4. Citation of publications reporting the discovery of fullerene C_{60} (H.W. Kroto et al., 1985), carbon nanotubes (S. Iijima, 1991) and graphene (K.S. Novoselov et al., 2004).

Soviet and Russian scientific schools traditionally maintained a high level of output and quite often reached advanced results in research into and the study of new forms of carbon (see Appendix). But Russian research has often not been seen by outside scientific authorities or been supported internally. Only 20 years after Russian scientists had published their anticipatory articles, in 1993, when the global flow of publications on fullerenes exceeded one thousand, was the Russian Ministry of Science and Technology Policy (as it was then) formed with a priority programme on "Fullerene and atomic clusters", which proved quite effective. Within the framework of this initiative, dozens of scientific teams from Moscow, Moscow region, St. Petersburg, Novosibirsk, Kazan, Nizhniy Novgorod, Ufa and Krasnoyarsk (a total of 63 in 1997) received financial support. Many of them became widely known and recognized in the world. The activity of the Russian Foundation for Basic Research (RFBR) has played a significant role in supporting the development and institutionalization of this research area. It is enough to note that the term "fullerene" was second only to the term "nanostructure" by frequency of occurrence in the terminological dictionary of RFBR "nano projects" for the period 1993–2006.[2] Russia occupied third place in the world in the number of publications in the field of fullerenes and their derivatives in 1996, but ceded it to China in 2005. It should be noted that a significant contribution was made by institutes of the RAS and MSU in advance of the umbrella research initiative, which also involved the main Russian scientific centres (in Moscow, St Petersburg, Novosibirsk, Chernogolovka, Troitsk etc.). In the history of the development of fullerene science, the publication contribution of the RAS is the greatest among scientific organizations of different countries. While Russian-authored publications were attracting relatively few citations on average (Table 1), eight of them have been cited over 100 times (i.e., had a significant impact on fullerene science development). Although Russia published its first article on carbon nanotubes immediately after Japan, subsequently it missed the shift of the global trend in favour of CNT and, as a result, was only fourteenth in the world by the number of publications produced in 2009. Revealingly, China began to study CNT later than Russia; however, support by the state allowed it to drastically increase its efforts in this area and take first place in the world by the number of annual publications. In general, CNT became a "favorite child" for receiving state support for NT; with nanotechnology initiatives starting in a number of countries in the early 2000s, the global flow of publications on CNT began to drastically increase (Figure 3).

In 2002 Russia began serious discussions about the need for prioritization of NT at the state level, which led five years later to the presidential initiative "Strategy for development of nano industry". Of course, such sluggishness of the state machine and the reactive nature of its research policy have had a significant negative impact on Russia's position in the international scientific competition. However, the decline of scientific productivity cannot be adequately assessed in isolation from the reduction of national research staff. Carbon nanostructures provide a good example of this. The "fullerene boom" occurred during the country's transition from a planned economy to a market, when our science was in very difficult circumstances. Nevertheless, relative success has been achieved, thanks to targeted government support, as well as research personnel still active from the Soviet era. About 1,800 Russian scientists took part in the development of fullerene science during the period 1991–2003, of which those active at the end of the period (those who in 2002–2003 published more than one article in this area) remained at 370 people.[7] The average age of the fifty most productive of them was 52 years, and of the first ten exceeded 56 years. Subsequently, the two youngest from the top ten emigrated to the USA, including a member of MSU, O.V. Boltalina, a member of the top 15 world ranking scientists in the field of fullerenes. In general, there was a significant outflow of world-class Russian scientists working in the field of carbon nanostructures to European countries, the USA and Japan. For example, the future Nobel laureates A.K. Geim and K.S. Novoselov left the country in 1990 and 1999, respectively. At one time this helped in establishing contacts with foreign colleagues, hence in obtaining international grants, which helped maintain a high level of research within the country. However, the departure of highly qualified scientists means losing implicit knowledge required for transfer to the younger generation and breaks the succession of generations and, as a result, affects the possibility of training new researchers. It is noteworthy that none of the emigrated Russian "stars" in the field of carbon nanostructures has submitted an application for the 150 million rouble "mega-grants" which the Russian government has allocated in 2010 to create world-class university laboratories.

The reduction of research staff in the NT area has played a noticeable role in the deterioration of scientific productivity in terms of bibliometric indicators. By the number of publications on fullerenes, Russia lost the third place that it occupied for a long time. In moving from researching fullerenes to the field of carbon nanotubes, Russia dropped to fourteenth place. Thanks to co-authorship in the discovery of graphene, Russia is second only to the UK by the average number of citations per publication (Table 1). However, Russia does not have a sufficiently broad scientific school, able to consolidate and develop this excellence (it occupied only the 11th place by the number of publications on graphene in 2009). Therefore, research output have been unstable and interrupted by the emigration of one or two highly productive scientists. It is obvious that the general deterioration of the "health" of national research personnel calls for a more thorough consideration of human resources when evaluating prospective research initiatives.

A short bibliometric view on nanophotonics

Failure to compete successfully on a broad front of research suggests that it might be worth concentrating on directions where prospects are more suited to available resources. Nanophotonics could be one of them. Nanophotonics (photonic crystals, metamaterials, quantum dot lasers, nanolasers, plasmonics) is a relatively new and rapidly developing direction of NT. Over the period 1999–2009, the number of publications on nanophotonics produced annually in the world has grown 7.3 times, whereas for NT as whole only 5.4 times. For this indicator, during this period Russia never fell below seventh place. The RAS is most active in conducting work in the field of nanophotonics (62% of publications), followed by MSU (37%) and the Scientific and Production Corporation "Vavilov State Optical Institute" (3%). Among world organizations, the RAS is behind only the Chinese Academy of Sciences (CAS) by the number of publications on nanophotonics for the entire period, but publications of the RAS are considerably more cited on average than publications of the CAS. 54% of Russian

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7 To calculate these values, the list of surveyed journals was supplemented by several dozen Russian scientific journals that are not handled in the SCI-expanded database.

articles in the field of nanophotonics have international co-authorship, which increases their citations. Co-authorship connects Russian scientists with representatives of thirty countries, and these connexions are closest with scientists from Germany, the USA and the UK Ten Russian scientists are members of the top hundred most productive authors in the field of nanophotonics. Among them five represent PTI RAS, four the International Laser Centre (ILC) of MSU and one the RAS Photochemistry Centre. A.M. Zheltikov from the ILC has the largest number of publications in the world (155) in this field. Among the top ten most productive Russian scientists in this field, N.N. Ledentsov (PTI RAS) has the best citation indices (average number of citations per author's publication is 32.6, h-index is 24). In this case, the leading scientific centres of the country have a good influx of young researchers from the St Petersburg Academic University, the RAS Nanotechnology Research and Education Centre and the Faculty of Physics of MSU.

Metamaterials—artificial structures with electromagnetic properties that are not present in nature—have recently became a hot theme worldwide. In the opinion of experts, the application of metamaterials in transformation optics could result in a revolution in different fields of science and technology. It is no mere chance that metamaterials (alongside CNT) are included in the top ten advances in materials science over the past fifty years.[8] In Russia, research in the field of metamaterials is maintained at a high level with the average number of citations per publication with Russian authors or co-authors (21.6 times per item) being above the global average (20.7 times per item). Two articles on metamaterials written by scientists from the Institute for the Physics of Microstructures and the Institute for Spectroscopy of the RAS have more than one hundred citations each. Our former compatriots, now working abroad, have world-famous names; for example, V.M. Shalaev (Purdue University, USA) and Y.S. Kivshar (Australian National University); they promote the development of international research collaboration with Russia. Their expertise and educational assistance can strengthen the capabilities of our country in promoting this topical area of research. Y.S. Kivshar, for example, helped to create a world-class laboratory at the National Research University of Information Technologies, Mechanics and Optics within the framework of a "mega-grant" from the Russian government.

Thus, in terms of bibliometric indicators as well as human resources, nanophotonics has good chances for priority development and competitive excellence.

Conclusion

For NT, as for the other emerging technologies, reliable and complete data on its economic results are not yet available. For this reason, bibliometric indicators, patent statistics etc. are often used to assess the competitive positions of countries. They give an idea of the scientific and technological foundation for future nanotechnology-driven innovations and for the economic development of a country.

Since nanotechnology is largely science-driven, the evaluation of scientific performance in terms of bibliometric indicators is of considerable interest. This study covers a 20-year period, which can be usefully divided into two halves. During the first half the priority of

[8] J. Wood, "The top ten advances in materials science". *Materials Today* **11** (2008) 40–45.

nanotechnology was developed in competition with other scientific fields. The second half is characterized by the priority development of NT on the part of an ever-increasing number of countries. Despite the socio-economic crisis in Russia in the 1990s, internal resources allowed and enabled Russian science to make an increasing contribution to world output of nano publications; even minimal state support in the area of fullerenes enabled world competitiveness until now. Unfortunately, Russia was not among the first countries to realize the potential of nanotechnology and organize priority financing at state level. A 5–7 year delay has led to a significant weakening of the competitive position of the country, as indicated by bibliometric rankings.

A major negative factor for the future of Russian NT research is human rather than financial, so that despite the intense funding since 2007, Russia in 2010 had already left the top ten countries (as indicated by the number of publications) and this will hamper Russia's entry into the group of world nanotechnology leaders, both in the medium and longer terms. At the same time Russia has demonstrated competitive abilities in several specializations, which are confirmed by recognized scientific achievements. The present analysis has revealed opportunities in nanophotonics and graphene research, which can be strengthened with the help of former Russian scientists working abroad. Another promising development is that researchers from Ufa have demonstrated methods for the creation of bulk nanostructured materials.

In the field of nanotechnology, Russia certainly has the ability to move from opinion-based policy towards evidence-based policy. Systematic bibliometric studies could justify this movement.

Appendix

Interest in the investigation of new carbon forms, which was epitomized by the calculated stability of the molecule C_{60} in the form of a truncated icosahedron, arose in Russia at the Institute of Organoelement Compounds (INEOS) of the Academy of Sciences of the USSR at the beginning of the 1970s.[9] Later, however, this excellent result was not developed and supported. Soviet scientists from the Institute of Physical Chemistry of the Academy of Sciences of the USSR observed CNT for the first time in an electron microscope in 1952. Fibres 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 too, research was not continued. Besides, the article describing this observation was published in a Soviet journal in the Russian language[10] and was not easily accessible to Western scientists. Now many researchers, including foreign ones, refer to this article. Russian scientists have once again turned to the subject of carbon nanotubes in the early 1990s.[11] We note that in 2004 a key contribution to the discovery of graphene was made by former and current Russian scientists from ITM RAS.

[9] D.A. Bochvar and E.G. Gal'pern, "Carbododecahedron, s-icosahedron, and carbo-s-icosahedron hypothetical systems". *Doklady Akademii Nauk SSSR* **209** (1973) 610–612.

[10] L.V. Radushkevich and V.M. Lukyanovich, "O strukture ugleroda, obrazuyushchegosya pri termicheskom razlozhenii okisi ugleroda na zheleznom kontakte" (in Russian). *Russian Journal of Physical Chemistry* **26** (1952) 88–95.

[11] L.A. Chernozatonskii, "Barrelenes / tubelenes - a new class of cage carbon molecules and its solids". *Physics Letters A* **166** (1992) 55–60.