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RESEARCH PAPER

Evaluating the performance of Russia in the research in nanotechnology

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Abstract The article analyzes the development of nano research in Russia during the years 1990–2010. To identify the contribution of Russia in nanoscience and to compare it with the contribution of other countries, we used the international multidisciplinary database Science Citation Index Expanded. Scientific performance is measured based on the growth rate of nano publications by countries and in the world, authorship patterns, indexes of international collaboration, etc. The indicators used are the national publication output, the total citations and the average citation per nano publication, the number and subject profile of highly cited nano publications; contribution and impact of Russian institutions. The article describes the current state and trends of nano research in Russia, their key players and the existing "centers of excellence." It also discusses some inconsistencies of Russia's science policy in the field of nanotechnology in light of the performed bibliometric study.

Keywords Nanotechnology · Nano research · Bibliometric analysis · Research evaluation · Science policy

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Introduction

In recent years, nanotechnology (NT) has become a "magnet" for research, investment, and policy. Nano research, started in the 1980s, moved along in an ascending manner in the 1990s and began to rise sharply in the 2000s. It attracts wide attention not only due to its strategic role in S & T development but also because future commercial rates are very high. Understanding the global processes of NT development and improving policy making require objective measurements. A useful measurement tool for research is bibliometrics. Creation of the Science Citation Index in the 1960s and the "science indicators" movement in the U.S. in the 1970s have contributed to the evolution of bibliometrics from a subdiscipline of library and information science to an evaluation tool for science policy and research management (Glänzel 2009). Following the U.S., the National Science Foundation (NSF) since 1972, publishes the report with analysis of the American science system twice a year; in the early 1990s, national facilities for monitoring the national science system were created in some European countries (van Leeuwen 2004). By that time, bibliometric indicators have become established for the evaluation and policy purposes.

Owing to their specificity, speed and scale of advancement in NT gave new incentives for bibliometric studies and evaluations at both national and supranational level. International acceptance of research-oriented definition of nanotechnology (Roco 2011a) also has played in this noticeable role. In the 2000s, especially in connection with prioritizing NT at state level by a significant number of countries, bibliometric studies became the field of growing activity for researchers, consulting firms, and government organizations. These studies focus on global nanorace, and also examine such themes as interdisciplinarities of NT, interrelations of nanoscience and nanotechnology, and path dependences of NT development and others (Kostoff et al. 2007; Shapira et al. 2010; Huang et al. 2011). The main milestones in the NT development as well as general trends for papers, patents, and investments are well represented in (Roco 2011a, b). In Russia, such works were carried out since the early 2000s and have been intensified to some extent after the launch of the national nanotechnology program in 2007 (Markusova et al. 2009; Terekhov 2009; Andrievski and Klychareva 2011). However, this is clearly not enough either for supporting in advance toward evidence-based policy or for a complete picture of Russia's place at the global nano landscape. In bibliometric studies of foreign researchers related to Russia, there are inaccuracies, e.g., owing to the poor knowledge of the names and the affiliations of Russia's research organizations (Liu et al. 2009). So, for extracting from the DB SCIE the consolidated data for the Russian Academy of Sciences (RAS) in this article, we had to combine more than 30 names of the RAS and its parts (departments and institutes). In tables 7 and 18 of Liu et al. (2009), the RAS was identified much more roughly. For example, in the Table 18 of Liu et al. (2009), the RAS's impact is understated because it is calculated without taking into account the contribution by such RAS institutes as: "AF Ioffe Phys Tech Institute" and "Boreskov Inst Catalysis." Distortions of this kind can lead to erroneous conclusions. All these emphasize that the current unfavorable situation in the Russian nanoanalytics should be corrected by conducting its own bibliometric studies according to modern transparent procedures.

The aim of this article is to offer a useful bibliometric tool for expanding evidence base under policy decisions in the field of NT. A result of its use is to provide updated information on current status and the main trends of nano research in Russia and in the world and to do some refinement of estimates of scientific activity and its participants in this field for our country. The obtained bibliometric data will also help to understand better the characteristics of the development of Russia's policy in nanotechnology and some of its inconsistencies. It is known that Russia was not among the first countries to recognize the potential of NT; it established its nanotechnology R&D program at the state level with a delay of about 5–7 years. However, back in the 1990s—difficult for Russian science due to socio-economic crisis—the government has supported a number of low-budget segmental programs related to NT, such as "Ultra dispersed (nano-) materials," "Physics of solid state nanostructures," and "Fullerenes and atomic clusters." Naturally, nanotechnology vision was still not holistic. In the Appendix, we give a brief chronology of the events which are important for the formation of Russia's policy in the field of NT. From this, it is followed that the Russian government considers the development of NT 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 this field. But, to what extent current R&D policy is adequate to these tasks, what are the consequences, e.g., of its protraction and selected accents for the competitiveness of Russia in NT? The bibliometric study gives certain empirical basis for the answers to these issues. To examine them in a broader context, we will introduce additionally some economic indicators and research-cadre dimension.

Methodology and data

Owing to its mass character, journal publications are most valuable when analyzing the size, structure, and sources of research. By quantity and quality of selected publications (articles, reviews, letters, proceeding papers, etc.), the Science Citation Index Expanded (SCIE) is the leading multidisciplinary database in the world. USSR, until 1992, and later Russia are represented in the database by about one million publications, which correspond to the 9th place among all countries. In view of these properties (mass, quality, and representation of Russia) DB SCIE (on the ISI Web of Knowledge platform) was chosen as the primary source of data for this study performed as of November 2011. Its methodology includes working out keyword list to search the database; implementation of bibliometric analysis and evaluation of nano research, both at macro (country) and at micro (institutes and researchers) levels; discussion of the findings of the bibliometric analysis, including an indication of failures of science policy in the field of nanotechnology.

In developing search strategy, a bibliometric investigator typically seeks to reach maximum coverage of the research domain, as it evolves over a time period, as well as to balance two risks: (a) to miss truly relevant publications and (b) retrieve irrelevant publications. Because of the emerging nature of nanotechnology, its breadth and degree of flux in the literature, there is a considerable variety of nanotechnology search formulations. A number of them are presented in (Braun et al. 1997; Kostoff et al. 2007; Liu et al. 2009; Huang et al. 2011). To the best of their sophistication, they lead, generally to search results which differ in terms of recall and precision. The most in-depth look at the problem has been shown in (Porter et al. 2008), where the multidimensional search nuances have been considered in detail. Our approach relies on a combination of the traditional nanotechnology search terminology and the search terms covering some new research directions, such as graphene or nanophotonics. Choosing to "title" keyword search means that we strived to form a core set of nanotechnology publications, giving significant weightage to the minimization of the above criterion (b).

Along with words with a "nano" prefix, we included the following search terms: "fullerene," "fullerite," "fullerid," "fullero*," "buckyball," "buckytube," "peapod," "quantum dot," "quantum well," "quantum wire," "QD laser," "bionano*," "dendrimer," "graphene," "photonic crystal," "metamaterial," and "plasmonics." Distinguishing chemical formulas—C60 (C-60) and C70 (C-70)—were also used. The excluded terms are "nanosecond," "nanogram," "nanoliter," "nanomolar," "nanoplankton," "NaNO2," and "NaNO3." Search in the DB SCIE by keywords, contained in the titles of publications, has identified 359,250 nano publications for the period 1990–2010 that constituted the initial sample for our analysis. This analysis is based on the traditional bibliometric indicators (publication counts or citations, Hirsch index (H-index), measures of collaboration, etc.) easily obtained by Web of Knowledge services for various subsets of the initial sample. In some cases, for more detailed comparisons, we calculated relative indicators using, in particular, economic data. Bibliometric evaluation at the microlevel requires notably careful verification. For this purpose, we disambiguated the names of organizations because the organizations are often registered in the DB SCIE under various names. For example, "AF Ioffe Phys Tech Inst," "AF Ioffe Physicotech Inst," and "AF Ioffe Inst" all refer to the same organization. The same thing we did for the names of authors of publications, e.g., Kop'ev PS and Kopev PS refer to the same person. We took into account the peculiarities of affiliations of local research institutes, for example, in calculating the aggregate ratings for the RAS (so, "Budker Inst Nucl Phys" is part of the RAS) and suchlike.

For the evaluative bibliometrics, it is the characteristic tendency to identify research of the "highest quality" or "scientific excellence." In keeping with this tendency, the article uses not only bibliometric impact scores based on the average values but also indicators reflecting the top of the citation distribution, such as the number of highly cited nano publications. Their subject profile indicates the place where there is scientific excellence. In discussing the results, we turn attention to human factor (serious crisis of research personnel in Russia) of deteriorating bibliometric indicators.

Results

Publication trends and citation indicators: country level

The scale of interest in the NT emphasizes participation in the research of scientists from more than 150 countries. First, we show the long-term trends of leading nations in nanotechnology and also some other nations, including the BRIC' members. Table 1 clearly demonstrates the "offensive" East to West on the number of nano publications, which is accompanied by quite significant changes in the rank positions of several countries. China, who was number seven in 1990, went out into the world's leaders by 2010, surpassing the U.S. A similar result, though with a shift of one year earlier, has been obtained before in (Kostoff 2012). India and Taiwan rose from 10th place to 6th place and from 15th place to 9th place, respectively. Starting from the scratch, South Korea and Iran have been able to rise during the same period to the 4th and 11th place, respectively. At the same time, Western countries have worsened their position: Germany (2↓5), the UK (4↓8), France (5↓7), Canada (8↓14), Italy (9↓13), Switzerland (11↓17), and the Netherlands (12↓20). Brazil dropped from 14th place in 1990 to the 18th place in 2010.

Table 1 Ranking countries by the number of nano publications

Country	No. of nano publications			Rank		
	1990	2010	1990–2010	1990	2010	1990–2010
USA	561	10,959	95,908	1	2	1
China	35	11,904	65,106	7	1	2
Japan	130	3,583	36,163	3	3	3
Germany	138	3,379	29,366	2	5	4
South Korea	0	3,459	19,656	–	4	5
France	82	2,311	19,346	5	7	6
UK	120	2,200	17,610	4	8	7
Russia[a]	40	1,693	15,528	6	10	8
India	22	2,945	13,596	10	6	9
Italy	23	1,395	10,576	9	13	10
Taiwan	7	1,741	10,459	15	9	11
Spain	6	1,529	9,347	16	12	12
Canada	27	1,142	8,429	8	14	13
Singapore	1	1,095	5,660	19	15	14
Australia	4	960	5,573	17	16	15
Switzerland	21	719	5,528	11	17	16
Poland	2	600	4,963	18	19	17
Netherlands	16	599	4,753	12	20	18
Sweden	12	564	4,435	13	21	19
Brazil	10	653	4,415	14	18	20
Iran	0	1,665	4,205	–	11	21
World	1,188	50,119	359,250			

[a] The USSR in 1990–1992

Participants of NT development on the global scale are the national scientific complexes of different sizes; so, to better understand of their strategies, we turn to relative indicators. Figures 1, 2, and 3 show that for the U.S. as the leader and the members of BRIC characteristic although in different degree is the growth of nanotechnology share in the total research output. For the U.S., this share did not exceed 3 % during the entire period, gaining about two percentage points after the adoption of the National Nanotechnology Initiative (NNI) (Fig. 1). By 2010, this became insufficient to keep the leadership in the production of nano publications. Interestingly, the world's largest scientific complex was focused on the NT not too strongly. China, India, and, to a lesser extent, Russia have surpassed the U.S. in this (Figs. 2, 3), putting their primary bets on the NT. By focusing 8.2 and 6.4 % of national scientific complexes on the NT, China and India have led their contribution to the world array of nano publications by 2010 to 23.8 and 5.9 %, respectively. Russia's contribution to the world array of nano publications in the period under review was subjected to significant change and, since 1997, went into a downward trend (Fig. 3). The following conditional calculation clearly shows Russia's lagging behind two leading partners in the BRIC. Note that Brazil till now is a weak participant of nano research. Under the current status quo, to push India from the 6th place, Russia would have to focus on the NT 11.7 % of its science complex. To take the first place, already 41.2 % of Russia's scientific complex would have to be focused on nano research. Significant contraction and deterioration of the national research community (Terekhov 2011) leave such targets beyond the possible.

In the scientific competition, not only the number of the produced publications but also their quality, measured by the citation, is important. According to Table 2, Russia is number twelve in the world on the total number of citations to all its nano publications and takes only 43rd place in the list of 65 countries with more than 100 nano publications on the average

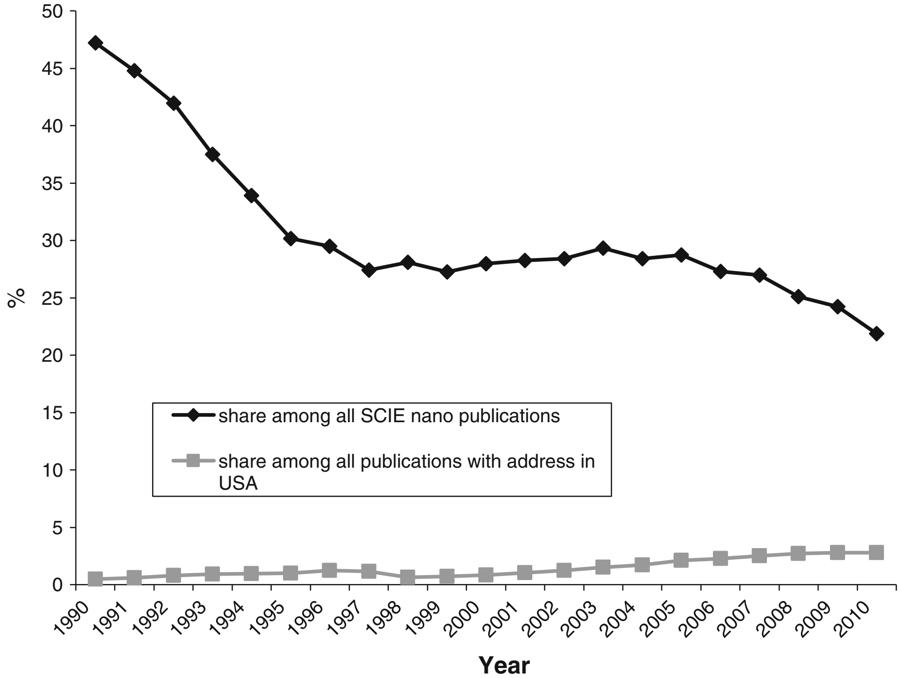

Fig. 1 Percentage share of nano publications having an address in USA among all American publications and among all SCIE nano publications year by year

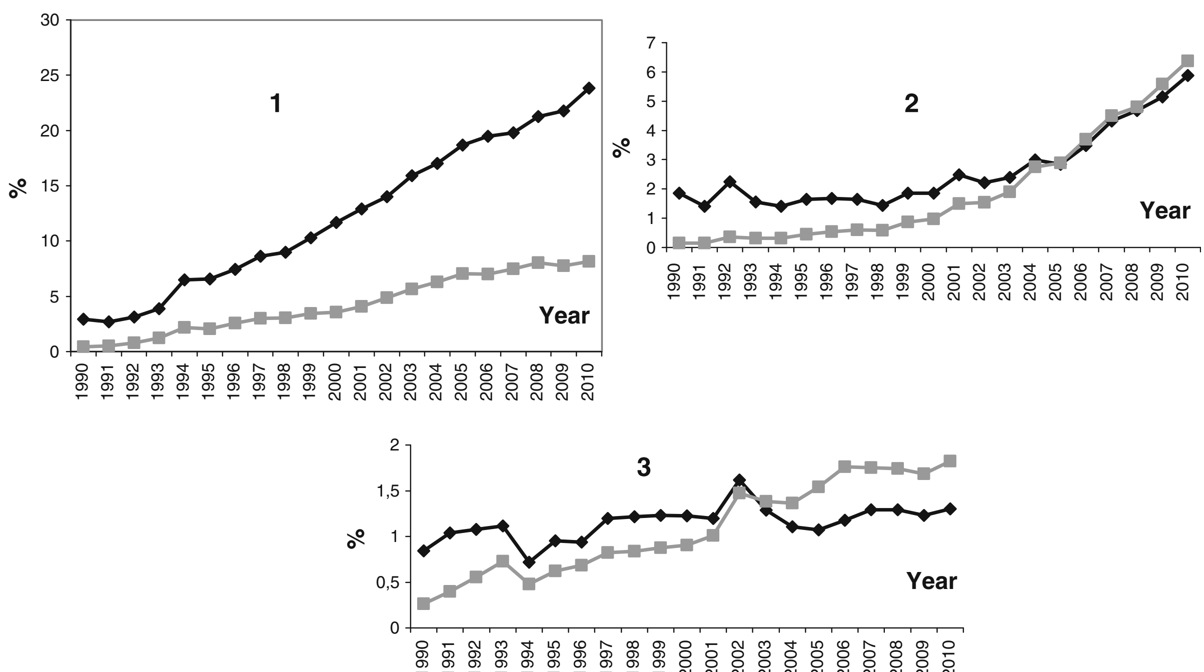

Fig. 2 Percentage share of nano publications produced by a country among all publications by this country and among all SCIE nano publications year by year: *1* China, *2* India, *3* Brazil (each pair of *curves* in the pictures is interpreted the same way as in Fig. 1)

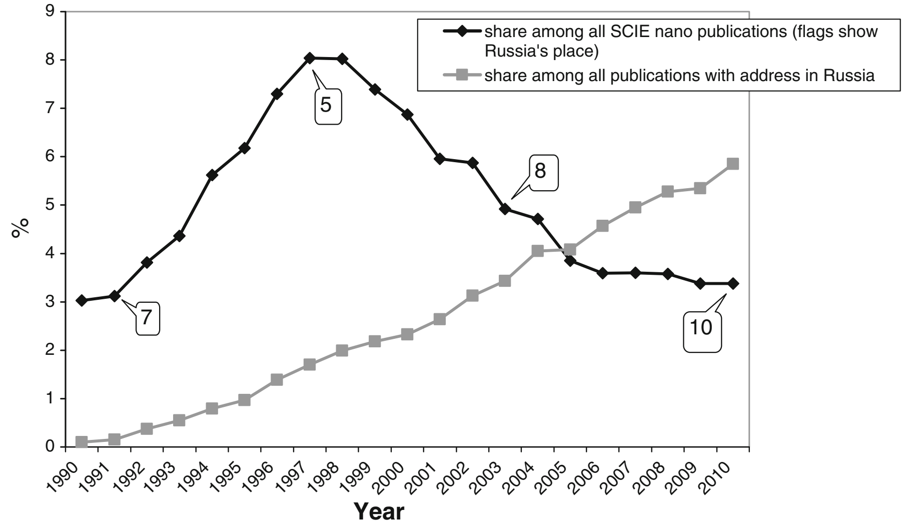

Fig. 3 Percentage share of nano publications having an address in Russia among all Russian publications and among all SCIE nano publications year by year

Table 2 Ranking countries by citation to nano publications

Rank	Country	Total citations to all nano publications	Average citations per nano publication	Rank countries according to average indicator[a]
1	USA	2,703,725	28.1	3
2	China	814,650	12.5	29
3	Germany	675,301	23.0	6
4	Japan	669,420	18.5	16
5	UK	424,026	24.1	5
6	France	405,515	21.0	10
7	South Korea	259,324	13.2	28
8	Italy	189,404	17.9	17
9	Spain	173,202	18.5	15
10	Switzerland	171,006	30.9	2
11	Canada	164,128	19.5	11
12	Russia	157,028	10.1	43
13	India	154,153	11.3	37
⋮	⋮	⋮	⋮	⋮
20	Brazil	59,798	13.5	26

[a] Among the 65 countries with >100 nano publications

number of citations per paper. By the first indicator, Russia lags in the BRIC behind China, and by the second indicator, lags behind India and Brazil too.

Let us turn further to the most cited nano publications, namely 199 nano publications with >1,000 citations. The first three rows in the Top 199 take articles which report about the discovery of carbon nanotubes (CNT)—11,499 citations at the time of the survey, of fullerenes—7,528, and of graphene—5,688 citations. 22 countries contributed to the world Top 199 nano publications. U.S. made the dominant contribution: 144 nano publications. Besides them, only United Kingdom, France, Netherlands, and Switzerland have made to the Top 199 greater contribution than to the whole array of nano publications. Four nano publications with more than 1,000 citations make Russia the 10th of the 22 countries. However, in the citation ranking of Top 199, these four publications occupy the worthy places. Three articles on graphene are on the 3rd, 14th, and 149th places, the review on the bulk nanostructured materials from severe plastic deformation is on the 36th place. In addition, another article on graphene co-authored with Russian, by the number of citations, is close to the threshold value (971 citations to the time of the survey). In Top 199, there are six nano publications from China and two from Brazil. Three Chinese and two Brazilian nano publications are devoted to CNT.

Important are the questions of efficiency of research performance, which we try to evaluate in terms of the numbers of publications/citations per unit of funding. Over the period 2004–2010 public spending on nanotechnology R&D in Russia corrected for PPP amounted to about $4,160 million. In calculating this value, we used estimates for 2004–2007 and report data on the implementation of the Program-2015 in the years 2008–2010. Since Rusnano does not support R&D, its funding was eliminated. NNI funding in the USA from 2004 to 2010 amounted to $10,002 million (Roco 2011a). The calculation of relative indicators for Russia gives on average 2.3 publications/16.3 citations per one million dollars. The similar indicators for the USA are 6.7 publications/129.0 citations per one million dollars. Thus, Russia is greatly inferior to the leader in the efficiency of research performance in the field of NT. One reason for this lies in the inefficiency of allocation of research funding. So, in 2009, the percentage of the RAS in public spending on nanotechnology R&D amounted to approximately 11 %. Nevertheless, in this year, the RAS contributed to 67.3 % of nano publications, which brought Russia 73.7 % of the citations. Thus, the relative indicators testify in favor of the RAS as the most effective sector nano research in Russia, which does not find, however, adequate reflection in the policy of scientific authorities of the country.

International collaboration of Russian scientists

Collaboration is an important feature of modern science. By their very nature, NT greatly strengthens interdisciplinary and international aspects of research collaboration. National programs of the NT development, as a rule, emphasize the expansion of international cooperation. In bibliometrics, co-authorship is the most studied indicator of collaboration. Joint nano publications with foreign colleagues will help us to identify intensity and pattern of international collaboration of Russian scientists and how co-authorship with some countries influences on the citations to Russian nano publications.

During the period under consideration 41.7 % of Russian nano publications were of international co-authorship which indicates the high integration of our nanoscience into the global one. Russia collaborated with more than 70 countries. 12.8 % of nano publications are co-authored with Germany, 7.8 % with the U.S., 4.7 % with France, 3.3 % with England, and 2.9 % with Japan. These are leading countries, collaboration with whom evidences (albeit indirectly) about a high level of Russian scientists' work. It is known that publications with international co-authors have a larger impact than nationally co-authored publications. This is confirmed in our case: if all nano publications with at least one Russian author have attracted on average 10.1 citations, then those that are written only by Russian authors—5.1 citations. Russian nano publications co-authored with England are cited most frequently: 42.3 times on average. It is followed by the Netherlands, 41.3; the U.S., 20.0; Germany, 18.6; France, 14.4; and Japan, 13.4 times on average. This is the kind of "scale" the quality of collaborative research between Russia and various countries on the basis of the citation to joint publications. Collaborative work on graphene de facto provides more highly citation of publications co-authored with England. Russian nano publications of 2008–2010, which were performed with the support of domestic and foreign funding agencies, allow additional comparisons in favor of international collaboration. For example, those, which were supported by the Russian Foundation for Basic Research (RFBR) (total 1,639 publications), have been cited by the time of the study on average 2.4 times. Those, which were supported by the American funding agencies, such as the NSF, National Institutes of Health, the U.S. Department of Energy, and others (total 175 publications), have been cited on average 10.3 times.

Figure 4 shows the dynamics of the international co-authorship of Russia in the field of NT. In light of the above data on citation decrease since 2006 the share of Russian nano publications with the international co-authorship in the figure can be interpreted as a poor signal.

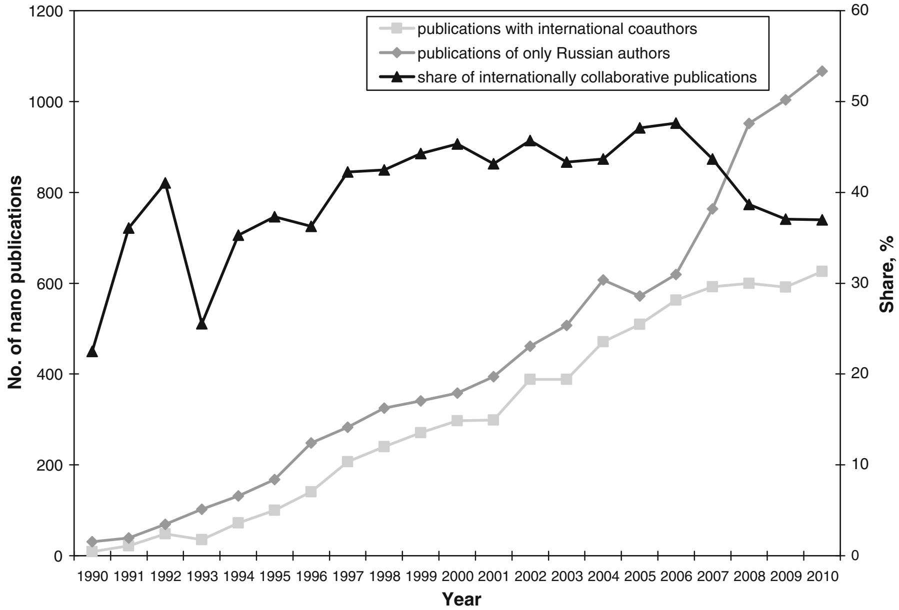

Fig. 4 Changing the number of Russian nano publications with and without international co-authorship (*left scale*) and the share first ones of total (*right scale*)

Table 3 Top 10 journals with the highest number of nano publications from Russia

Rank	Journal	Country	IF-2010	No. of nano publications
1	*Physics of the Solid State*	Russia	0.727	824
2	*Physical Review B*	USA	3.774	815
3	*Semiconductors*	Russia	0.605	665
4	*JETP Letters*	Russia	1.557	509
5	*Technical Physics Letters*	Russia	0.496	462
6	*Russian Chemical Bulletin*	Russia	0.629	264
7	*Applied Physics Letters*	USA	3.841	247
8	*Journal of Experimental and Theoretic Physics*	Russia	1.450	239
9	*Inorganic Materials*	Russia	0.416	230
10	*Fullerenes Nanotubes and Carbon Nanostructures*	USA	0.631	201

Evaluating quality of nano research and its participants

About the quality of the array of Russian nano publications, it can be judged in the first approximation from the list and the Impact Factor (IF) of journals in which they are published. The total number of such journals is over 500. Top 10 journals on the number of nano publications are given in Table 3. Seven of the Top 10 is Russian journals with small values of IF, i.e., en masse, our scientists published in journals whose impact by the evaluation of the Institute for Scientific Information (ISI) of the U.S. is relatively low. However, Russia has 9 and 13 nano publications in prestigious journals *Nature* (IF = 36.101) and *Science* (31.364), respectively. A further 56 were published in seven of the Top 10 Journals in Nanoscience & Nanotechnology according to the ISI classification in 2008: *Nano Letters* (IF = 10.371), *ACS Nano* (5.472), *Small* (6.525), *Biosensors & Bioelectronics* (5.143), *Nature Nanotechnology* (20.571), *Nanomedicine* (6.093), *Plasmonics* (3.488).

More justified indicator of the publications influence is their citation. Citation distributions are strongly skewed. In our case, 23.4 % of Russian nano publications have not received citations at all (Table 4). 79.4 % of them have attracted few citations, namely, citations lower than average. 165 nano publications

Table 4 Distribution of citations to Russian nano publications

No. of citations	No. of nano publications	Total no. of citations
0	3,636	0
1	2,211	2,211
2	1,556	3,112
3	1,257	3,771
4	919	3,676
5	681	3,405
6	583	3,498
7	482	3,374
8	382	3,056
9	324	2,916
10	297	2,970
11–20	1,573	23,022
21–30	651	16,222
31–40	310	10,805
41–50	184	8,395
51–60	100	5,570
61–70	95	6,186
71–80	56	4,266
81–90	34	2,913
91–100	32	3,062
>100	165	44,598
Total	15,528	157,028
Average		10.1
Median		2.5

(1.1 %) with >100 citations have contributed almost 30 % of the total citations to all nano publications In its entirety, the actual distribution in Table 4 corresponds to the "20/80 law" where 20 % of publications account for 80 % citations.

The group of 165 highly cited nano publications (Top 165) is of interest for thematic analysis and to identify the Russian "centers of excellence"[1] in the field of NT. 25.5 % of publications in Top 165 are devoted to carbon nanostructures (fullerenes, nanotubes, graphene, nanodiamonds, nanofibers, and onions). This includes work on fullerene, conducted in the Nesmeyanov Institute of Organoelement Compounds RAS since the late 1960s, work on superhard fullerite in the FSI Technological Institute for Superhard and Novel Carbon Materials, CNTs at the Lomonosov Moscow State University (MSU), etc. 13 publications in the Top 165 that received a total 14,348 citations is devoted to graphene. 10 most cited among 13 publications were written by scientists from the Institute of Microelectronics Technology and High Purity Materials (IMT) RAS in co-authorship with scientists from England and the Netherlands (co-authors in two articles additionally were scientists from the U.S. and Germany). All publications appeared in prestigious journals: *Nature*, *Nature Materials*, *Nature Physics*, *Science* (2), *Proceedings of the National Academy of Sciences of the USA*, *Nano Letters* (2), *Physical Review Letters* (2). Co-authors in yet three highly cited publications on graphene together with foreign colleagues were scientists from the Landau Institute for Theoretic Physics (ITP) RAS.

The IMT RAS has in the Top 165 yet the six publications (on quantum dots, nanotubes, and nano-photonics) and the average citation to nano publications of this Institute (96.6 citations) is a record. On this indicator (36.6 citations on average) also stands out the Ufa State Aviation Technical University (USATU), the research of which on the bulk nanostructured materials led by famous scientist R.Z. Valiev can be attributed to the "centers of excellence." In addition to the aforementioned review of the bulk nanostructured materials, which occupies the 36th place in the world ranking Top 199, the Top 165 Russian nano publications includes yet seven publications by this author, some of which co-authored with scientists from the U.S. and Germany. With the indicator, equal to 23.7 citations on average per one nano publication, ITP RAS is the third among Russian organizations. According to this indicator, three of our research organizations are comparable with leading foreign universities: Harvard (73.6 citations on average), Stanford (53.1), Cambridge (27.5), and Oxford (25.6); however, almost an order of magnitude inferior to them by the number of nano publications. Hence, in particular, the comparison of the quality of research at the organizational level requires more than one indicator follows. However, the identification of highly cited organizations and research groups provides useful information for the formation of the priorities of science policy.

The largest percentage of nano publications in the Top 165 (37.6 %) is dealing with semiconductor nanostructures. By the number of publications in this research direction, Russia did not fall below the 7th, and from 1997 to 2002 occupied the 4th place in the

[1] Operationally by this term we shall mean any organization, research team, or scientific school, which stably produces highly cited publications on a specific topic.

world. This high for our country result has been achieved thanks to a scientific school, founded by Academician Z. I. Alferov in the Ioffe Physical-Technical Institute (PTI) RAS. The heyday of this school (by bibliometric indicators) was at the end of the 1990s, e.g., in 1999, 10 of its members (with average age of 38.7 years) were part of the 100 most productive authors of the world in the field of NT. At the same time was founded by the St. Petersburg Academic University, which purposefully prepares research personnel for NT. It is worth remembering that in 2000 Z. I. Alferov was awarded the Nobel Prize in physics.

Nanophotonics (12.1 % of publications in the Top 165) are quite closely related to the semiconductor nanostructures. The research community has noticed three publications on the metamaterials ("hot" theme for nanophotonics now), which was written by scientists from the Institute for Physics of Microstructure, the Institute for Spectroscopy (IS) and the Shubnikov Institute of Crystallography (IC) of the RAS. Russian studies in the direction of "nano-bio-med" (9 publications in the Top 165) also have become visible on the world nano landscape. Such organizations as the Blokhin Russian Cancer Research Center of the Russian Academy of Medical Sciences (RAMS), the Sechenov Moscow Medical Academy, the Moscow Research Institute of Medical Ecology, the Research Institute of Human Morphology RAMS, the MSU, and the Shemyakin-Ovchinnikov Institute of Bioorganic Chemistry (IBC) RAS have made contribution to the performance these works. Work of the IBC RAS (together with scientists from France and Belarus) on the use of fluorescent quantum dots as biomarkers, published in the *Analytical Biochemistry* in 2004, has attracted 124 citing publications, average citation rates of which in the DB SCIE, in turn, was 82.2 times. From this, we can conclude that this work has made a strong enough scientific resonance. The citing publications to yet two publications from the Top 165 have attracted more than 80 citations on average. These are (a) the article in *Journal of Physical Chemistry B* on nanocrystal superlattice of gold nanoparticles prepared by different methods, written by scientists from the Boreskov Institute of Catalysis SB RAS with colleagues from the U.S. and (b) the note in *Physical Review B* about band-edge absorption and luminescence of nonspherical nanocrystals, written by scientists from the Saint Petersburg State Polytechnical University with colleagues from Germany. So, using the secondary indicator of this kind, we were able additionally to emphasize the high impact of three Russian publications concerning the preparation and useful properties of nanocrystals.

Table 5 Top 10 Russian institutions by the number of nano publications, 1990–2010

Rank	Institution/ organizational structure	No. of nano publications	Average citations per nano publication
1	PTI RAS	2,516	13.4
2	MSU	2,188	9.0
3	SPbSU	695	5.3
4	ISSP RAS	560	11.9
5	ISP SB RAS	529	8.9
6	LPI RAS	448	10.0
7	IPCP RAS	372	6.7
8	IC SB RAS	322	12.1
9	IS RAS	299	12.3
10	SIC SOI	290	7.3
	RAS	10,547	10.5
	HEIs	5,034	8.0
	SRIs & SRCs	963	7.7

SPbSU Saint Petersburg State University, *ISP SB RAS* Rzhanov Institute of Semiconductor Physics of the Siberian Branch of the RAS, *LPI RAS* Lebedev Physical Institute of the RAS, *IPCP RAS* Institute of Problems of Chemical Physics of the RAS, *IC SB RAS* Boreskov Institute of Catalysis of the Siberian Branch of the RAS, *SIC SOI* The Scientific and Industrial Corporation 'Vavilov State Optical Institute', *HEIs* Higher Education Institutions, *SRIs & SRCs* Sectoral Research Institutes and State Research Centers

It should be especially emphasized that international co-authorship increases not only the average citations to Russian nano publications but also the probability for them to become highly cited. So, about 42 % of all Russian nano publications have international co-authorship; but, in the Top 165, their share is reaching up to 86 % already. Priority is given to the collaboration with Germany, the U.S., and the UK.

We proceed to the evaluation of institutional and individual participants in nano research. Table 5 shows that at the meso level, reflecting a sectoral organization of Russian science, the RAS leads: it has the largest output as well as the average number of citations to its own nano publications. The seven institutes of the RAS are in the top ten research organizations by the number of nano publications for the entire period. Academic researchers have contributed to 122 out of the Top 165 nano publications. The leaders here are the PTI RAS, the IMT RAS, and the Institute of Solid State Physics (ISSP) RAS. However, international comparisons reduce optimism, e.g., comparable in size, the Chinese Academy of Sciences (CAS) has produced over the entire period more nano publications than did the RAS and with a greater average citation (16.4 times) than in the RAS (10.5 times).

Since 2006, a purposeful policy of scientific authorities of the country became a shift to the center of gravity of research activities in universities. Awarding the status of research university, which provides additional funding, has strengthened role of bibliometric indicators. The implementation of this policy was synchronized with (and even was caused by) prioritizing NT at the state level; the reaction of bibliometric indicators exactly in this field is very interesting. According to Table 6, by the number of publications in 2008–2010, the MSU ahead of the PTI RAS, as well the Novosibirsk State University (NSU) entered to the top ten institutions. It would seem that the application of this policy quickly gave the desired effect. However, the famous scientist from the ITP RAS, the reviewer in the *Physical Review* (Feigelman 2012), noticed that behind the "increasing research" at the State University Moscow Institute of Physics and Technology (MIPT), allegedly under influence of the recent cash infusions, it is worth only a change in the practice of specification by the scientists who teach their institutional affiliations at the University in part-time. Indeed, in his articles, made mainly in the Institutes of the RAS, these scientists began to add the address of MIPT. Such unintended effects of the use of bibliometric indicators may have occurred in the case of the MSU and the NSU, which are known for their close relationship with the RAS. At least, this requires further investigation.

Table 6 Top 10 Russian institutions by the number of nano publications, 2008–2010

Rank	Institution	No. of nano publications	Average citations per nano publication	H-index
1	MSU	733	3.1	19
2	PTI RAS	525	3.5	17
3	SPbSU	270	2.9	12
4	ISSP RAS	143	3.4	11
5	IPCP RAS	143	3.2	8
6	ISP SB RAS	132	2.5	9
7	IC SB RAS	120	3.4	10
8	LPI RAS	120	2.0	7
9	NSU	87	2.1	5
10	IGIC RAS	86	1.6	5

NSU Novosibirsk State University, *IGIC RAS* Kurnakov Institute of General and Inorganic Chemistry of the RAS

Be that, as it may in recent years, the RAS institutes continue to hold a leadership role in nano research (Table 6). The best indicators on publications and citations are also owned by scientists from the RAS (Table 7). Two of them, S. V. Morozov and V. G. Dubrovskii, the most frequently cited for a short-time interval, are doing research in the field of graphene and semiconductor nanostructures, respectively.

Let us note the low corporate engagement in research output in Russia (only in 75 nano publications in 2008–2010). This sector is presented mainly by SMEs, many of which are research spin-offs. The most active among them are the CJSC Innovations of Leningrad Institutes and Enterprises, St Petersburg (carbon nanotechnology) and OOO "NPK Nanosystem," Moscow (pharmaceutics) with 20 and 4 publications, respectively, for three years. NT-MDT Co., Zelenograd (nanotechnology instrumentation) and OOO "Kintech Lab," Moscow (nanotechnology, development of new materials) have participated in three nano publications each. Only a few large national companies, such as JSC Plastpolymer (St Petersburg), JSC Siberian Chemical Plant (Seversk, Tomsk region), JSC Severstal (Cherepovets), and CJSC Novosibirsk Electrode Plant (Linyovo, Novosibirsk region), minimally marked in the list of nano publications for the three-year period. This contrasts with the situation in the world, where some 17,600 companies have published about 52,100 scientific articles on the NT from 1990 to 2008 (Shapira et al. 2011).

Findings and discussion

The study period (1990–2010 years) could be usefully divided into two stages. During the first stage (1990s), the priority of nanotechnology was developed in competition with other scientific fields. The second stage (2000s) is characterized by the priority

Table 7 The most productive Russian scientists in the field of NT, 2008-2010

Name of scientist	Institution	Research directions	No. of nano publications	Average citations per nano publication	H-index
1. Lozovik YE	IS RAS	Physics of nanostructures; nanooptics	46	3.03	6
2. Ovid'ko IA	IPME RAS	Mechanics of nanomaterials	45	5.29	10
3. Tretyakov YD	DMS MSU	Functional nanomaterials	41	1.54	4
4. Obraztsova ED	GPI RAS	Carbon nanostructures	41	3.88	6
5. Zheltikov AM	DP MSU	Nanophotonics	31	5.35	7
6. Ivanov SV	PTI RAS	Semiconductor nanostructures	30	2.30	5
7. Ivanov VK	IGIC RAS	Functional nanomaterials	29	1.76	3
8. Okotrub AV	NIIC SB RAS	Carbon nanostructures	28	1.82	4
9. Dubrovskii VG	PTI RAS	Semiconductor nanostructures	26	11.46	9
10. Cirlin GE	PTI RAS	Semiconductor nanostructures	26	7.31	8
Morozov SV	IMT RAS	Graphene	11	139.09	7

IPME RAS Institute of Problems of Mechanical Engineering of the RAS, *DMS MSU* Department of Materials Science of the MSU, *GPI RAS* Prokhorov General Physics Institute of the RAS, *DP MSU* Department of Physics of the MSU, *NIIC SB RAS* Nikolaev Institute of Inorganic Chemistry of the Siberian Branch of the RAS

development of NT on the part of an ever-increasing number of countries. Despite the socioeconomic crisis in Russia in 1990s, internal resources allowed Russian science to make increasing contribution to the world output of nano publications. The year 1997 was a turning point in this trend. Since then, the percentage share of Russian nano publications in the DB SCIE has been steadily declining, putting Russia by 2010 on the brink of relegation from the top ten countries for this indicator. The negative trend was the result of prolonged underfunding of science and the brain drain, as well as was due to the competitive advantages of other countries, ahead of Russia in prioritizing NT at the state level. Even a massive increase in investment in the NT, which started since 2008, was unable to reverse this trend, as the determining factor by this moment became not a financial, but human factor. Scientific staff potential to increase focusing on the Russian scientific complex on the NT is increasingly depleting. For example, the research workforce of the RAS, which provides about 68 % of all Russian nano publications, has grown old on average with 43 years in 1990 to 51 years in 2008. The age distribution of this contingent has a “dip” in the age interval, which is the most favorable to the scientific productivity, and also a long “tail” after 60 years (now the weight of the “tail” is about 37 % of entire contingent) (Terekhov 2011). Add that the average age of the ten most productive in the NT Russian scientists in 2010 was 53.1 years, which exceeded the average equivalent of 1999 by 14.4 years. Herewith, if the Russian ten of 1999 entered in the Top 100 of the most productive world scientists in the field of NT, then the Russian ten of 2010 did not get even into the world Top 500. The age distribution of the professional personnel of the CAS is much more favorable in terms of scientific productivity. So, if the share of researchers at the age of 35 years or less in the RAS equals to about 25 %, then in the CAS, it exceeds 43 % (CAS (Chinese Academy of Sciences) 2011). Obviously, to continue to compete at the forefront of nanoscience, Russia will have to prepare a new generation of researchers, but it is a long process, even under the best economic conditions. However, Russian nano scientist diaspora, which has formed abroad on account of external brain drain, could help this process, as well as to the NT development on the whole. It includes, in particular, the world-class scientists, who emigrated from Russia in different years, such as the Nobel Laureates A. K. Geim and K. S. Novoselov (specialists on graphene; University of Manchester), O. V. Boltalina (specialist on fullerenes; Colorado State University, USA), V. M. Shalaev (specialist on nanophotonics; Purdue University, USA), Y. S. Kivshar (specialist on metamaterials; Australian National University), etc. Their departure from the country (of each in his time) meant the loss of tacit knowledge required to transfer the younger generation, and depletion of nutrient juices for the innovation system. As noted Kostoff (2012), for supporting and accelerating technology and engineering development, it is very important to have available highly qualified specialists to address the research issues which inevitably arise in the course of development. This is particularly true for nanotechnology with its non-linear relationships between science and technology. Now, owing to the new government policy to encourage brain circulation, the diaspora could strengthen Russia's capabilities in the NT development and in the solution of cadre problems through expertise and educational assistance of its representatives. Some of them are already included in this work. K. S. Novoselov, for example, has provided advice to Rusnano, V. M. Shalaev participates in the expertise of the Skolkovo projects, O. V. Boltalina continues to cooperate with the MSU. Y. S. Kivshar helps 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.

Concerning the total number of citations to all nano publications, Russia takes the twelfth place; however, by the average number of citations per nano publication, it is located only at the forty-third place. One explanation is that it is due to large number of publications in Russian journals, translated into English, with low impact factor. This, in particular, causes the high share of Russian nano publications, having zero- and low citation counts, e.g., 37.7 % of these have less than 10 % of the mean citation count. Top 165 highly cited Russian nano publications (with >100 citations per each) present the opposite end of the actual citation distribution. It is well known that the international co-authorship increases the citation impact of the publications. But, for the Russian nano publications, this relationship manifests itself with particular force. Indeed, the nano publication in co-authorship with foreign counterparts is cited on an average of 3.4 times more often than just the Russian authors. Share of nano publications with international co-authorship in Top 165 is 86 %, while a similar share in the total mass of Russian nano publications is 42 %. The most "advantageous" in terms of citation over the analyzed period was the collaboration with the England, the U.S., and Germany. To this, we add the works, supported by U.S. funding agencies are cited several times more often than those, which were supported by the Russian ones. Hence, it is fair to conclude that this international collaboration in many ways makes the Russian works visible on the global nano landscape.

Based on thematic analysis of the Top 165, we identified three "centers of excellence" namely in the field of (1) semiconductor nanostructures, (2) graphene, and (3) bulk nanostructured materials. The first "center" presents a full-fledged scientific school, the formation of which dates back to the early 1970s, when the study of semiconductor heterostructures has become the rapidly growing direction in semiconductor physics. Since then, founded by Academician Z. I. Alferov at the PTI RAS school successfully develops this direction in our country and the world. In the early 1980s, there was a transition in heterostructures on nanosize; to date, the semiconductor nanostructures (quantum wells, dots, and wires) are already involved in commercializing NT in Russia. The second "center" fits into the main stream in global nano research of the last 8 years. In 2010, our former compatriots, A. K. Geim and K. S. Novoselov (scientists from the ISSP RAS and IMT RAS, respectively)[2], received the Nobel Prize in Physics "for groundbreaking experiments regarding the two-dimensional material graphene." At the moment, graphene is considered the best material for NT, e.g. for prospective nanoelectronics. Thanks to co-authorship in discovery of it, Russia is the second only to the UK by the average citations per publication in this field. However, our country does not have a sufficiently broad scientific school, able to consolidate and develop this excellence. It occupied only 11th place by the number of publications on graphene in 2009. Besides, in publications, which have provided Russia remarkable harvest of citations, along with A. K. Geim and K. S. Novoselov constantly participated single scientist from the IMT RAS, S. V. Morozov. Only in three out of mentioned ten highly cited publications on graphene, three other members of the IMT RAS were co-authors together with him. Therefore, the situation may change due to the emigration one or two highly productive scientists, and this does not allow to consider durable such "center." New direction in the physical materials science, which led to the formation of the third "center," arose in the early 1990s. It was then that researchers from the USATU proposed and justified the method of severe plastic deformation for the production of bulk nanostructured materials. Currently, this research is successfully continuing in

[2] The first of them left Russia in 1990, and the second-in 1999.

the Institute for Physics of Advanced Materials USATU led by Professor R. Z. Valiev. Of great interest are the developments of the Institute of bulk nanostructured metals and alloys for innovative applications, e.g., in biomedicine, aviation, and energetics. Some Russian publications in other nanotechnology directions have also had a significant impact, in terms of collecting citations at the first or at the second step of the citation chain. This concerns, e.g., metamaterials or nanocrystals and their useful properties, including biomedicine.

The RAS is the key organization participant of the nano research in Russia, both in the number and quality of publications. Its institutes and researchers preponderate in domestic ratings on various bibliometric indicators. It has the highest ratio of publications/citations per unit of funding. External comparisons are not as good, e.g., the CAS (Chinese analog of the RAS) has produced over the entire period more nano publications than did the RAS and with a greater average citation than in the RAS. Nevertheless, according to the bibliometric indicators, institutes, such as PTI RAS, IMT RAS, and ITP RAS, are fairly internationally competitive in nano research. Therefore, it looks like a double standard, when scientific authorities of the country declare the need to bet on a "strong" in enhancing the competitiveness of domestic science, and at the same time continue to fund universities in a more preferred mode. For today, exactly the RAS with its institutes, despite staffing problems, remain more "strong" in the nanotechnology research. The merits of universities in this do not justify the enhanced investment yet.

Now, returning to the question of efficiency, this time paying attention to its economic aspects. Programmable efficiency of investment in the NT development (now, considering the expenditure of Rusnano) can be simplistically assessed, comparing the cumulative investment over the period 2008–2015 under the Program-2015 ($\sim$\$10.6 B) and the expected nanotechnology market size ($\sim$\$30 B in 2015). The ratio is 2.8 to 1. Consider the similar eight-year period from the start of the US NNI (2001–2008). According to the Lux Research, total cumulative funding for NT over this period amounted to about \$28 B (PCAST (President's Council of Advisors on Science and Technology) 2010). In turn, the value of products incorporating nanotechnology as the key component reached to about \$80 B in 2008 (Roco 2011a). The output-input ratio in this case is about the same. However, the characteristic difference in approaches may be observed. According to expert opinion (CRS (Congressional Research Service) 2008), the US NNI investment since its inception (at least 30 % of total investment in NT) has been focused on basic research. Foundational research has provided a good basis for a shift at the next step to more new commercial products of the 2nd and the 3rd generation. As a result, the expected size of the nanotechnology market in the U.S. by 2015 will be about \$400 B, which will significantly increase the return on investment (Roco 2011a). The Program-2015 emphasis is in favor of the commercialization of applied results—the accelerated creation of nano industry in Russia. In our estimate, funding the basic research will not exceed 6 % of the total investment under this Program. After a long period of the significant decline of the Russia's share in the world nano research output, such approach seems erroneous. The former Minister of Education and Science, A. A. Fursenko, indirectly confirmed this, admitting in February 2012: "we have actually exhausted of the existing reserve of basic science, therefore we need generating qualitatively new scientific knowledge" (MES (Ministry of Education and Science of the Russian Federation) 2012). Earlier, in his interview to the press on the topic of nanotechnology Academician, Z. I. Alferov said more definitely: "promising developments, including R&D have almost gone. They have been exhausted, the last thing that was left, has been picked up by the Rusnano" (Alferov 2011). Not surprisingly that in 2011 the nanoenabled products in Russia by 86 % consisted of elementary nano products and conventional goods manufactured using nanoenabled processes (Gokhberg 2012). The latter means mainly the petroleum products produced using nano catalysts.

Conclusion

This study has shed light on some facts of Russia's policy in the NT field.

1. Inflexibility and reactive nature of this policy. This was evident still in the case of carbon nanostructures; then, there was a delayed support by the state of fullerene direction, and later the lack of response to changeover global trend on

more promising carbon nanotubes (Terekhov 2009). Russia established the nanotechnology R&D program at the state level after the second generation of active nanotechnology products had come to market (Roco 2011b). A 5–7 year delay has led to a significant weakening of the competitive position of the country, as indicated bibliometric rankings. Even large investments in NT, since 2008, could not overcome the long-term decline of Russia's percentage contribution in the world nano publications output[3]. A considerable contribution to this was made by the crisis of national research personnel, the number and quality of which is essential to maintaining a competitive edge in this science-driven field. Serious generation gap will be supplemented by the impact of negative demographic trends of the 1990s (from 1987 to 1997, the birth rate in Russia was reduced by half) that will deplete the reserve for replenishment of research personnel in the next decade. These problems have already been partly understood and included in the policy actions (e.g., encourage international mobility and support of young scientists), but it remains unclear when these actions can give practical effect. The delay has also led to a lack of accumulated investment and a lower return on investment for the planning horizon compared to the more advanced competitors.

2. Wrong emphasis in current policy. When elaborating the strategy of NT development, its definition as research oriented in essence has not been accepted. Preliminary extensive bibliometric and patent studies to identify the global trends and positioning Russia were not carried out. Apparently, this has led to an overestimation of existing scientific reserve and pushed to make the main bet on commercializing applied developments. Of course, this was not without the nanohype and lobbying by interest groups. Given the weak involvement of the corporate sector into research activities in the NT field, the special state corporation Rusnano was founded, which, however also not be obliged to directly support the R&D. In these circumstances, it looked ill founded to shift the center of gravity of research activities from the more productive RAS into as yet weak research universities; rather, had to look integrative forms of nano research development. The results of this approach were not slow to follow (see the above quotations of A. A. Fursenko and Z. I. Alferov). The situation must be corrected. Funding for basic research needs is to be enhanced because they expand the cognition horizons and provide the foundation for new fundamental initiatives. This is particularly true for such science-driven area such as nanotechnology. From these positions funding of academic science in Russia should be increased.

3. The nanotechnology R&D policy should focus more on the areas where the country can achieve advanced development. According to the present study, Russia is not able to support a broad front and the pace of nano research on the level of leaders. At the same time, it 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 the former Russian scientists working abroad. We have the well-known scientific school in the field of semiconductor nanostructures with good reproduction of research personnel. Scientists from Ufa have developed original methods for the creation of bulk nanostructured materials.

The cause of many failures in science policy is that the expert judgments frequently prevail over the principle of evidence-based policy. Systematic application of the bibliometric methods in the monitoring and evaluation of national science system has not yet become an established practice in Russia. But recently, the Russian specialists in science policy increasingly began to use this tool under funding allocation. However, experience shows that bibliometric indicators, along with the advantages (objectivity, comparability, and gripe of the picture in whole), have also a number of limitations. So, the validity of the indicators depends on their level of aggregation. Unintended effects of the use of bibliometric indicators can occur , e.g., in the case of MIPT. Hither you can add tendentious use and misuse of bibliometric date. There are quite a few examples and the reasons of this, one of which is—evaluating bodies

[3] In 2011, that is not covered in this study, Russia has fallen by this indicator at 11th place.

are the same as or dependent on the implementing agencies—very common in Russia. Hence, it would be wrong to rely on the bibliometrics as a relatively simple and inexpensive alternative to peer review for evaluating research performance. Better to combine the two methods in such a way that the strength of the first compensates for the limitations of the second, and vice versa (Moed 2007).

Appendix

Since 2002, under the influence of the adoption by leading countries, the nanotechnology initiatives debates on the problems of NT development in Russia, finally started. Collegium of the Ministry of Industry and Science (then) dedicated the state of affairs in Russia in the field of NT chaired by the Minister I. I. Klebanov held in March 2002. Wider discussion took place in the same year at the scientific session of the General Meeting of the RAS, where Nobel laureate Z. I. Alferov made a key report "Nanostructures and nanotechnology." Hearings in the State Duma on the theme "Nanotechnology—the problems of development and training" under Z. I. Alferov's chairmanship was held in 2004. In general, it was stated that in the field of NT, Russia has serious knowledge stock and even scientific results, outstripping the world level, but powerful acceleration and competitiveness with the leading countries require the substantial public support. In 2006, in his Annual Address to the Federal Assembly, President V. V. Putin said "Russia has the potential to become one of the leaders in the field of nanotechnology…I believe we must take rapid steps to draw up and adopt an effective program in this field" (President of the Russian Federation 2006). In the same year, the priority "Industry of nanosystems and nanomaterials" was introduced in the approved by V. V. Putin list of "Priority Areas of Development of Science, Technology, and Equipment in the Russian Federation." Finally, in April 2007, President V. V. Putin signed a presidential initiative "Strategy of nanoindustry development" (President of the Russian Federation 2007). Creation of a national nanoindustry has been recognized in it as the key strategic priority which defines new approaches to transform the domestic industry. The strategy covers the period of up to 20 years, during which, as a result, the phase development of nanotechnology is supposed to create a fundamentally new technological basis of the economy in Russia. In the medium term, the main instruments of state policy in the field of NT are

- Program of Nanoindustry Development in the Russian Federation until 2015 (Program-2015);
- Federal Targeted Program (FTP) "Development of the Nanoindustry Infrastructure in the Russian Federation for 2008–2011";
- Others are the federal targeted, regional, branch, and departmental programs providing financing of developments in the field of NT and bringing their results into industrial production.

The Program-2015 is a coordination program and accumulates other programs, where especially important is FTP "Research and Development in Priority Fields for the Development of Russia's S&T Complex for 2007–2013" (Government of the Russian Federation 2008). In 2007, the Russian Corporation of Nanotechnologies (Rusnano) was founded as the key coordinator of innovation policy designed to commercialize promising R&D projects in the field of NT. The Russian Federation made initial asset contribution in Rusnano with the amount of 130 billion rubles. Russia will channel by 2015 into NT development with a total 318 billion rubles (approx. $10.6 billion). Volume of sales of the Russian nanoenabled products by 2015 should reach 900 billion rubles (approx. $30 billion).

In 2010, Rosnano has been transformed into joint-stock company and got the state guarantee for debt financing (bonds issuance) in the amount of 180 billion rubles. It must be specially stressed that the funding of R&D is not the objective function of Rusnano. Additional information about the environment of national policy in the NT field, as well as the time line for other nano-related initiatives, can be found in Klochikhin (2011).

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