BUILDING BALANCED AND ADOPTIVE SECTORAL INNOVATION SYSTEM IN NANOTECHNOLOGY TO ACCELERATE SCIENTIFIC&TECHNOLOGICAL BREAKTHROUGHS AND IMPROVE HUMAN CONDITIONS[1]

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Introduction

The concept of controlling matter at the atomic level—which is at the heart of nanotechnologies promise—was first publicly articulated in 1959 by physicist Richard Feynman in a speech given at Caltech entitled "There's Plenty of Room at the Bottom," (Feynman 1959). American futurist K. Eric Drexler is widely credited with popularizing the term in the mainstream. In his 1986 book, "Engines of Creation," Drexler envisioned a world in which tiny machines or "assemblers" are able to build other structures with exquisite precision by physically manipulating individual atoms. If such control were technically achievable, then atom-by-atom construction of larger objects would be a whole new way of making materials and could have the capacity to usher to a *second Industrial revolution*. It would be a revolution with even more profound societal impacts than the first one (Drexler, 1991).

Nanotechnology promises to be one of the defining yet controversial innovations of the 21st century. By promising smaller, lighter and faster devices, using fewer raw materials and consuming less energy, nanotechnology has potentially substantial benefits from a sustainability perspective. These nanoscale structures and devices may have unique chemical, electrical, magnetic, optical or biological properties. According to 'Towards a European Strategy for Nanotechnology', nanotechnology has important implications for most, if not all industrial sectors. It particularly highlights medicine, information, energy, materials, manufacturing, instrumentation, food, water, the environment and security as key areas.

Few technologies have attracted so much funding globally as nanotechnology has the last 5-10 years. There is a global race to take the lead in what many expect to be the next industrial

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revolution (Luther, 2004a, Lux Research 2005). Currently there is in fact very little substantial knowledge on the dynamics and specificity of nanotechnology development; we try to specify this S&T domain. Thus, nanotechnology is an emerging, disruptive technology in an early very exploratory creative stage. This is a fast developing multidisciplinary S&T domain, which is expected to change all sectors of economy, social needs and precondition the emergency of new markets and possibly new sectors of economy. As a new emerging field its areas of application remain not well defined but it is already clear that the same scientific breakthroughs might be used in different sectors of economy. The consequences both beneficial and adverse of technological innovations' implementation are not well explored as well as the impact of nanotech on other S&T domains, on the structural shifts in economy, on the NIS and other sectoral innovation systems. In addition, social values and cultural issues will have a special impact on nanotechnology development (Gaponenko, 2006a, 2006c).

The very early stage of nanotechnology development provides a perfect opportunity for the study of "emergence" of sectoral system of innovation and production (SIS), i.e. the first phase of SIS formation. One has to note that on the one hand SIS in Nanotech is emerging as a result of self-organization of different actors (setting up of spin-offs companies by scholars or venture funds by transnational corporations, and the like) but on another hand it is driven by the actions implemented by public authorities.

Methodological background

Nanotechnologies themselves produce the challenges to methodological approaches for SIS analyzing, to the Foresight's methodology, economy, R&D and educational systems and public at large (Gaponenko, 2006d). One has to address to different theories to understand the emergence of SIS in Nanotech. We'll try to outline some key points of basic theories and approaches, which might be helpful for the understanding of SIS emergence in Nanotech.

A *concept of sectoral system of innovation and production* developed by Franco Malerba serves like a background for the exploration of SIS emergence in Nanotech. Malerba defines a sectoral system of innovation and production as a "set of new and established products for specific uses and the set of agents carrying out market and non-market interactions for the creation, production and sale of those products. A sectoral system has a knowledge base, technologies, inputs and an (existing and potential) demand. The agents composing the sectoral system are organizations and individuals (e.g. consumers, entrepreneurs, scientists). Organizations may be firms (e.g. users, producers and input suppliers) and non-firm organizations (e.g. universities, financial institutions, government agencies, trade-unions, or technical associations), including sub-units of larger organizations (e.g. R-D or production departments) and groups of organizations (e.g. industry associations). Agents are characterized by specific learning processes, competences, beliefs, objectives, organizational structures and behaviors. They interact through processes of communication, exchange, cooperation, competition and command, and their interactions are shaped by institutions (rules and regulations). Over time a sectoral system undergoes processes of change and transformation through the coevolution of its various elements" (Malerba, 2002, p. 6-7). This concept provides a methodological background for the exploration of key elements of SIS in Nanotech and stress that SIS might be understood like a coevolution of its various elements.

A central place in an *evolutionary approach* is occupied by three economic key processes driving economic change: processes of variety creation in technologies, products, firms and organizations, processes of replication, that generate inertia and continuity in the system and processes of selection, that reduce variety in the economic system (Nelson,1995; Metcalfe,1998). Today it is a puzzle how these key processes will play in the new emerging SIS; there is not enough knowledge and information yet for the analyses, however SIS in Nanotech provides a unique opportunity for the analyses of these processes at different stages of SIS formation and development.

Concept of sectoral system of innovation and production and Evolutionary theory provide a methodological background for the analyses of path dependence in an emerging SIS, for drawing a line around the boundary of sectoral system, for the analyzing its key elements in evolutionary context, for the exploration of emergence of networks, learning and technological regime, mechanisms of interaction and SIS impact on the national system of innovation (NIS).

Innovation cycles theories and studies reason that some changes in technology have so revolutionary impacts on the economy that they will result in a techno-economic paradigm change (Perez, 2000, 2002). Nanotechnology is widely considered as being a disruptive technology (Bresnahan and Trajtenberg 1995, Gaponenko, 2006a). Neo-schumpeterian theory emphasize the relationship between economic and technological development arguing that such fundamental technological changes bring discontinuity in economic development but also serve like a drivers of economic growth at a new cycle of development (Freeman, 1982; Gaponenko, 1997b; Gaponenko, 1994). Nanotechnology is considering to be a disruptive technology, opening the sixth Kondratieff cycle; we think, that it is likely that they will bring revolutionary changes in the knowledge base of

NIS, technological mode of production in many sectors of economy, may create the basis for entirely new industries, will change the needs, system of value and mode of consumption of average citizen.

The innovation cycle literature generally points to two major phases of technology evolution (Tushman et al., 1986, Utterback, 1994). The first phase follows the emergence of a new technological paradigm and is characterized by rapid and radical change and high uncertainty. The second phase is made up of consolidation and stabilization processes around a dominant design. It looks like that nanotechnology are still at the first phase. Technological evolution being considered within a long period, one can single out repeated growth, stagnation and transition intervals that replace each other. Each phase of a long-wave cycle has its specific features and regularities of evolution (Gaponenko, 1994). Industrial transition is likely to take 20-30 years if nanotechnology follows similar gestation times as other general-purpose technologies (Freeman and Loucã, 2001). Hence the present embryonic, fluid stage of nanotechnology development appears analogous to that of the two other major general-purpose technologies, biotechnology and ICT, 25-30 years ago (Freeman and Loucã, 2001). A question in nano innovation research is whether we can expect similar paths of development of nanotechnology as with these preceding general purpose technologies? (Darby and Zucker, 2003). We think that as far as the rhythm of technological evolution is accelerating, one can wait much more rapid changes than in case of ICT and biotechnology.

Any new Kondratieff cycle is marked by the increasing complexity of a system (Gaponenko 1994, 1997a, 2006b); therefore one has to address to *Complexity theory*. Cardinal inference of the Complexity is that of increasing complexity of the system itself while transferring from one order to a new one. In this case, the diversity of elements of the system increases, the mechanisms of interaction between various system elements became more complicated (Gaponenko, 1997a). Thus, one can wait that the diversity of institutional structures in the national system of innovaion (R&D organizations, knowledge transfer enterprises, companies, and the like, i.e. firms and non-ferm organizations) will increase, their mode of performance, mechanisms of collaboration with other organizations, and the learning regime will be changed as well.

At the very heart of innovation system research lies the idea that innovation results from the coevolution of technology, organizations and institutions (Freeman, 1987; Freeman, 1995; Lundvall, 1988, 1992 (ed.); Nelson, 1993; Perez, 2000, Freeman and Loucã, 2001, Lundvall, 2005). A core characteristic of the innovation system approach is thus the explicit focus on institution formation and transformation. What kind of institutional changes in SIS and in NIS will be pushed by multidisciplinary, cross-sectoral and disruptive nanotechnologies?

Thus innovation cycles and Complexity theories provide guidance for the analyses of path creation dynamics, for the understanding the formation of sectoral innovation systems. The results show that nanotech development is currently in an extremely fluid stage of development where technologies are little defined nor agreed upon. Extremely early, however, nanotechnology is becoming specific, path dependence is established and search trajectories are set.

Coupling Kondratieff cycles, Evolutionary, Complexity theories as well as the concept of the sectoral system of innovation and production provide the theoretical and methodological background vital for the exploration paths creation dynamic and understanding the formation of SIS in Nanotech at the very early stage.

Specific characteristics of SIS in Nanotechnology

At the very early stage one can already outline the specific characteristics of SIS in Nanotech. The very embryonic stage of SIS in Nanotech is marked by the institutional gaps, setting up of new institutional structures (firms and non-firm organizations)), emergence of networks, learning regime and technologies' consolidation.

Knowledge base is an engine of SIS formation in Nanotech. Malerba pointed out that the knowledge base of SIS "differ across sectors and greatly affect the innovative activities, the organization and the behavior of firms and other agents within a sector" (Malerba, 2002, p. 7). What are specific characteristics of knowledge base of SIS in Nanotech? First of all it is multidisciplinary, cross-sectoral, is characterized by the enormous thematic breadth; the most important sub-disciplines are applied physics, material science, physical chemistry, physics of condensed matter, chemistry and molecular biology. One may already observe the structural shifts from physics towards material science, polymer chemistry and chemistry (Heinz, 2006, p.4). Research in nano S&T field is not purely fundamental or fully applied (Heinz, 2006, p.12). Today basic and applied science is concentrated mainly in the public sector. One may already observe some common trends and actions on the way of formation of the sectoral R&D system around the world: setting up of interdisciplinary nanotech research centers and centers of excellence (Gaponenko, 2006a). In addition too, nano-research require a specific and expensive scientific equipment therefore public authorities do their best to provide both public research organizations and private sector by the necessary equipment and instrument. Multidisciplinary knowledge base pushes multidisciplinary and overlapping networks in SIS (Heinz, 2006).

Technological base of SIS in Nanotech is not coherent. Nanotechnology appears today is not technology but a diverse and unfocused technological conglomerate. Many refer to nanotechnology in the plural (Royal Society, 2004). Research interest in the nanoscale exists in many disciplines opening new grounds for multidisciplinarity and combination of scientific paradigms. Despite the huge and still rising R&D investments in nanotechnology worldwide development is still at the experimental stage and the level of commercialization is very limited (Wood and Geldart, 2003, Lux Research 2004, Cientifica 2003, Bundesministerium für Bildung und Forschung, 2004). Major barriers remain in turning slow laboratory experiments into large scale, reliable and economic methods (Luther 2004b). We know still very little about how the nanotechnological platform is going to consolidate. Nanotechnology conforms to a pattern of science based innovation identified by Rosenberg (1982) where scientific instruments play an interactive role between science and technology. The early development of instrumentation precedes and facilitates scientific developments, which in turn stimulates technological development and downstream commercial applications in "carrier industries" (Andersen, 2006).

SIS in Nanotech is marked by emergence of non-firm organizations such as financial institutions, interdepartmental governmental agencies for actions' coordination as well as technology transfer organizations. A special role at the initial stage play venture funds and business incubators (Gaponenko, 2006a).

The US National Science Foundation predicts that the total global market for nanotechnology products and services will reach $1 trillion by 2010, which represents nearly 10% of the present US gross domestic product and will require a work force of 2 million. Nowadays the market of nanotechnologies is still at the early stage but it is expected that it will grow rapidly. Analyzing its trends we can emphasize some of its peculiarities:

- special role play small and new enterprises, mainly spin-offs;
- close linkages of companies with research centers and universities;
- some regional differences at the markets: in North America the part of small and new enterprises is extremely high, in Europe research institutes and universities prevail.

Although the SIS in Nanotech is at the initial stage one can already outline some common measures implemented around the world in framework of National Nanotech Initiatives to build a balanced and adoptive SIS. Some measures are oriented on the institutional gaps (setting up interdisciplinary research centers or knowledge transfer enterprises, investment in research infrastructure and educational centers); another ones are focused on the supporting networks and information infrastructure development.

Nanotechnology : Global and regional trends

Globally R&D expenditures in nanotechnology grow dramatically. Total global investment for the 2003 is estimated at $7,74 billion but for the year 2006 – $12,35 billion; while public R&D expenditures increased 2.0 times during this period, the corporate ones increased 2,65 times (Fig.1).

The private sector investment in nanotechnology has flourished in the past years with an estimated $5.3 billion for 2006 compared to $880 million invested in 2002. Both the public and

Fig.1. Global public and private investments in nanotechnology, 2003-2006 (U.S. $ million)

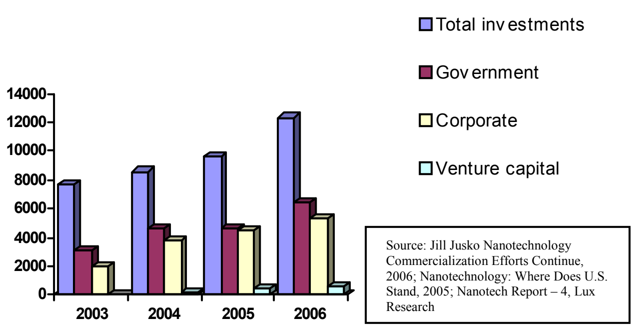


Fig.2. Public and privat investments in nanotechnology by regions, 2005 (U.S. $ billion)

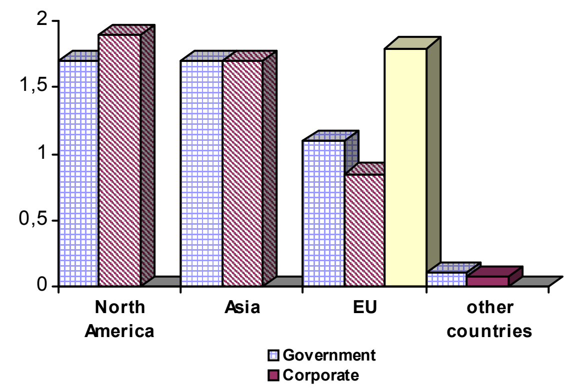
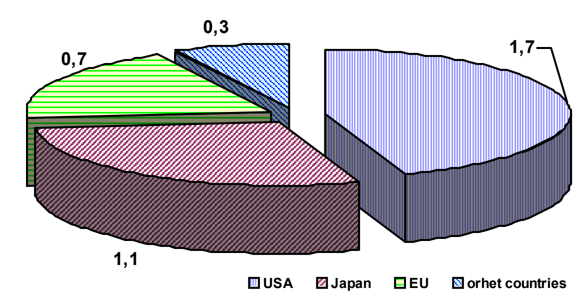
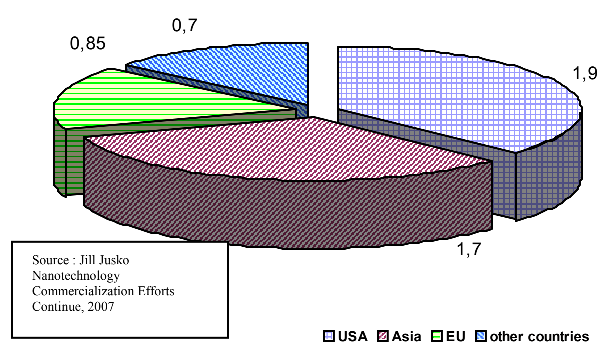


Fig.3. Corporate R&D expenditures by the regions of the world, 2004, (U.S. $ billion)



Source :Nanotechnology: Where Does U.S. Stand, 2005

Fig.4. Corporate R&D expenditures by the regions of the world, 2005 (U.S. $ billion)



private investment has helped boost producer and end user attention in the field of nanotechnology. Oracle, Microsoft and Best Software all have been highly interested on the potential of nano-based computing. All are potentially looking at the application service provider (ASP) model of business and especially to the doors that nanotechnology opens to mid-size and smaller companies. Hewlett Packard, IBM, and Intel are all racing to create a "Nanochip" and/or small hard drives that would turn previous findings obsolete. This sector has the potential to grow, since market giants like Dell, Microsoft, Samsung, Motorola, Sony, Lucent and AT&T are all investing and purchasing the new technology in order to potentially satisfy the customer needs.

Globally venture capital investment in Nanotechnology market totaled $200 million for the year 2004 and about $650 million for the year 2006. Lux research reported that VC investments are highly concentrated; since 1998 only 143 nanotech start-ups have received institutional venture capital funding (out of about 1,500 that operate globally). USA is a world leader regarding the both corporate and venture capital investment in the field (Fig.2.- Fig.4.).

Thus one can to outline the following trends in the field; first public R&D expenditures grow faster than the budget appropriation on R&D; the second, although nano-market is at the initial stage corporate R&D expenditures grow faster than the public ones and in North America they exceed the public investment in nanotechnology (Fig.2); the third, recently in global corporate R&D expenditures one may observer the shift in favor of Asia Pacific countries and so called "other countries" (Fig.3-4).

What drives nano—market and push corporations to invest in nano-scale research? We have outlined the following key drivers: market expectations, growing competition at the electronic market, energy problems' aggregation, promise of some social issues solution (cancer, diabetes, early diagnostic, and the like) as well as lack of innovation out of "nano" which potentially could yield significant revenue.

Some studies have already shown that nontech companies drive collaborations with public R&D organizations and invest in nano-scale research, for example 85% of American SMEs at the nano-market had collaborations with universities (Lux research, 2005). It is not surprising and conditioned by the multidisciplinarity of nano-research, lack of skills for interdisciplinary research in framework of companies. In addition too high-tech companies (mainly spin-offs) have their roots in R&D organizations therefore they have got linkages and "common language" with scholars.

However, the expectations are accompanied by risks and barriers. Using interviews like a tool we have outlined the following key barriers on the way of corporate expenditures grow: still small and fragmented nano-market, risks associated with the raising up cultural, ethical and religious issues on the way of market development, lack of information about and understanding of future trends, lack of skills and underdeveloped educational system, lack of information about and understanding of R&D output.

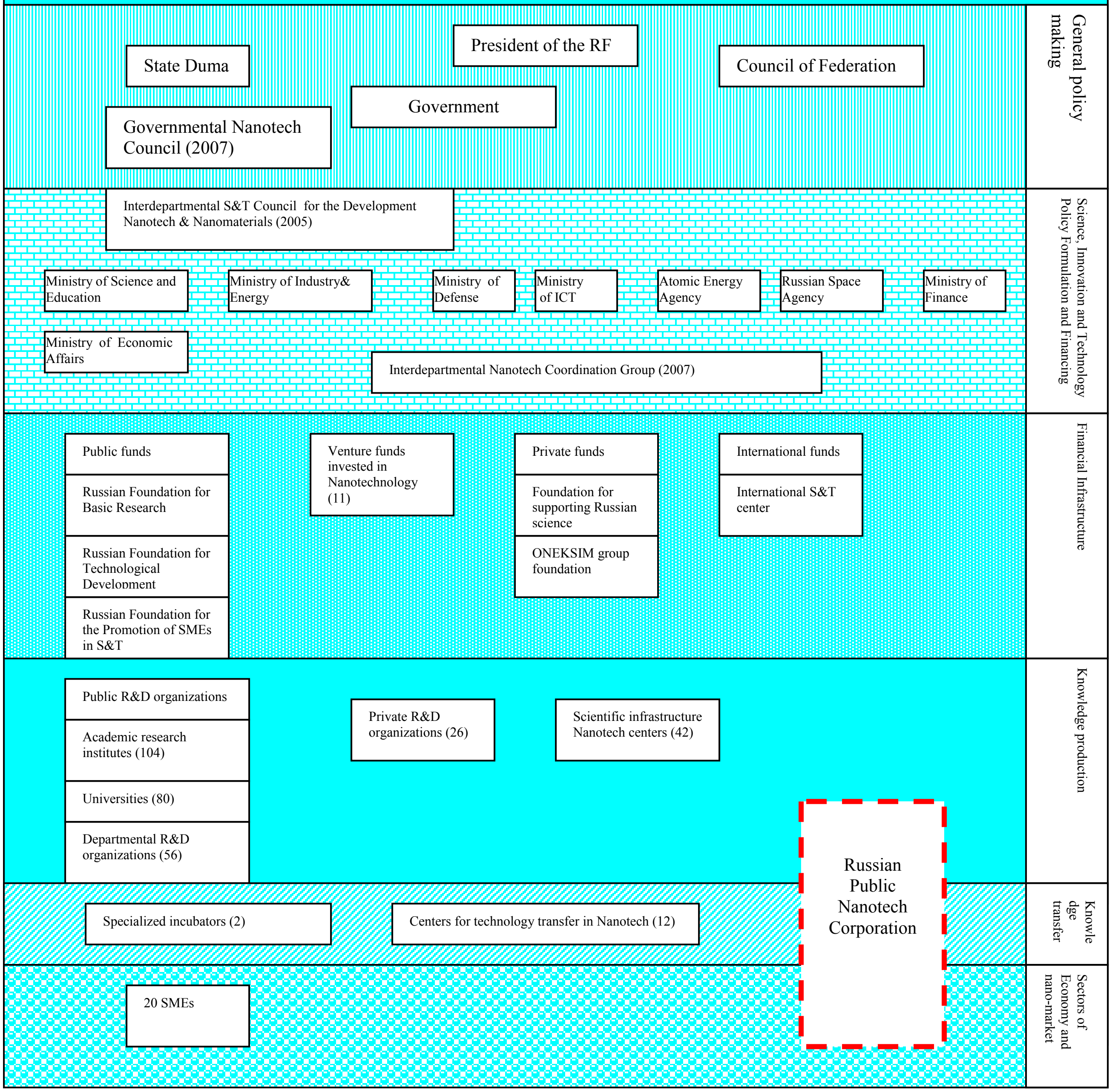
Russian specific characteristic of SIS in nanotechnology

Russian SIS in Nanotech has been emerged as a result of self-organization and actions implemented by public authorities; one has to point out that governmental actions for a long time were mainly focused on the supporting of sectoral R&D system and development scientific infrastructure. Fig 5. represents the institutional set up of Russian SIS in Nanotech. Outlining the SIS institutional environment help to clarify the role of the various governmental agencies, the wait of public and private sectors in funding and carrying out R&D and the role of R&D-funding institutions and those that perform related functions (such as technology transfer, and the like).

Institutional map consists of six layers, each with different functions. The top layer comprises the general policy-making bodies: the President of the Russian Federation, the Council of Federation and State Duma, which pay a key role in setting broad policy directions. The second layer represents institutions that formulate and implement science, innovation and technology policy. One may observe that during the last three years a special Council under the Government of the Russian Federation and Interdepartmental S&T Council were set up for the coordination of actions in nano-area. However the responsibility for the implemented actions is still washed out as far as the coordination of actions between federal and regional level authorities is still weak.

The third layer comprises the public, semipublic foundations and private investors, which, together with federal and regional authorities, finance and support the production and implementation of innovations. As we mentioned earlier a special role in nanotechnology development plays venture capital. One has to note that the numbers of venture funds invested in nanotechnology has increased more than 5 times during a year; in 2006, there were only two venture funds invested in nanotechnology. In addition too, the ONEKSIM group has launched a private foundation for the supporting hydrogen energy and nanotechnology.

Fig. 5. Russian SIS in Nanotech Institutional Set up



One has to note that Russian corporations were rather passive in nano-field. However the setting up the private foundation by ONEKSIM group could change the trends, impact the expectations of private sectors, their beliefs and behavior. It is remarkable that Russia has rather strong positions in energy sector but is nor strong enough in nano-energy. ONEKSIM group invests precisely in nano-energy; therefore some path dependence trends one may already observe in Russian SIS at the early stage. It looks like that space technologies and aircraft will be also nanotech consumers; these are sectors where Russia has also rather strong positions and where public and private sector already express interest to nanotech. Therefore path-dependence is already visible in Russian emerging SIS in Nanotech.

The fourth layer comprises the organizations that carry out R&D. R&D organizations are concentrated mainly in the public sector (about 90%) and within public sector- in the Russian Academy of Sciences (RAS). The fifth layer includes the organizations facilitating technology diffusion, while the sixth layer represent companies at the Russian nano-market.

Russian SIS in Nanotech is imbalanced. For many years special attention was paid to nanoscience development but innovation infrastructure remains underdeveloped.

Russian nanoscience is financed from different sources. Ministry of Science and Education (MSE), Ministry of Industry and Energy, Ministry of Defence, Ministry of Public Health, Russian Academy of Sciences, Russian Academy of Medical Sciences, Russian Foundation of Fundamental

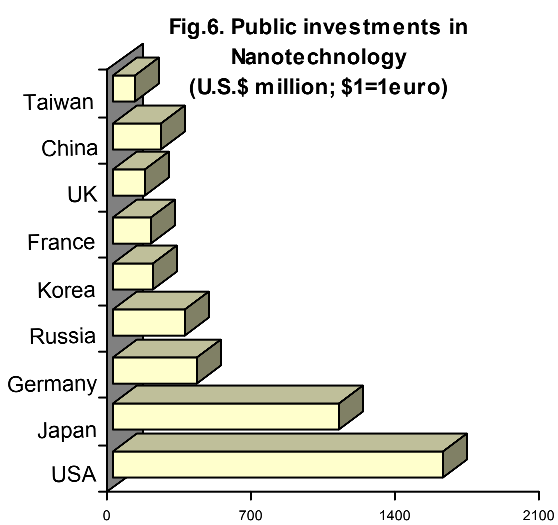


Fig.6. Public investments in Nanotechnology (U.S.$ million; $1=1euro)

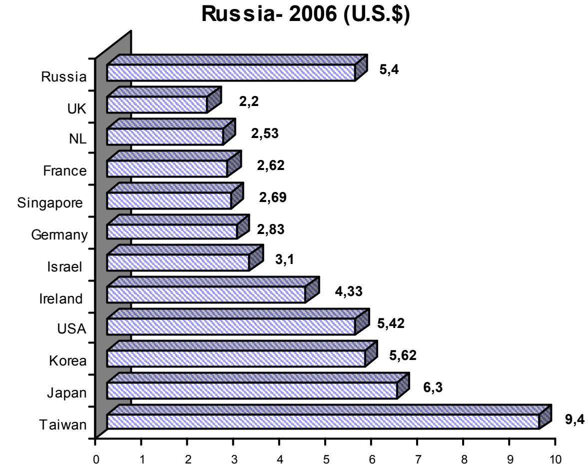


Fig. 7. Government nanotech funding per capita at purchasing-power parity, 2004; Russia- 2006 (U.S.$)

Research (RFFR) are the key agencies supported nanoscience. It was evaluated that, in 2006, the budget appropriations on nanoscience were about $US 350 mill. Therefore Russian public investments into nanoscience are less than budget appropriations of USA, Japan and EU but higher than public investments of many Asia- Pacific and some EU countries (see Fig. 6, 7.). R&D projects are supported in framework of various national and departmental programs: “National Technological Base” (2002- 2006); “ Ultradispersion Nanomaterials and Nanotechnologies”; “Nanoelectronic of Armed Forces of the RF till 2010”; “Development of R&D Capacity of High School” (2006- 2008); “Low- dimensional Quantum Structures”; “Nanomaterials and Supra-molecular Systems”; “Physics of Solid Nanostructures”; “R&D in Priority Directions of S&T

(critical technologies)" (this program supported by the MSE of the RF has a special subprogram "Industry of Nanosystems and Nanomaterials"). Some regional authorities (in particular in Moscow and Tomsk) also support nanoscience in framework of regional and municipal programs. However R&D are not coordinated between different departments and federal and regional power structures as well. One may observer the duplication of R&D, on the one part, and lack of information about the outputs, on another part.

In 2005 and 2006, MSE of the Russian Federation gave a special attention to the development of scientific and information infrastructure in nanofield. There are 42 centres in the Russian Federation where research facilities might be used by public and private sectors (much more than in other countries). In 2005, MSE allocated about $US 30 mill. for the purchase of equipment for the centres, however one may observe a low demand from the direction of both public and private sectors for the implementation of these facilities.

As we have mentioned earlier R&D organizations are concentrated in the Russian Academy of Sciences. RAS finance seven interdisciplinary programs and drives the multidisciplinary

Fig. 8. Break down of R&D Organizations by Sectors (in %)

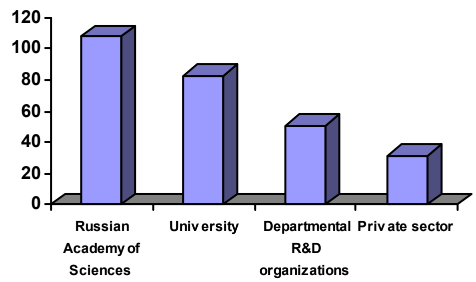
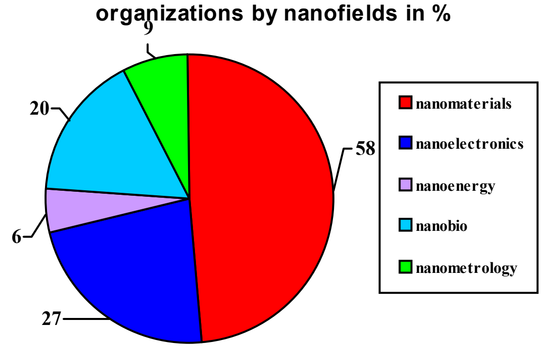


Fig. 9. Break down of R&D organizations by nanofields in %



networks. Another remarkable

feature of R&D capacity is the concentration of R&D in nanomaterials (more than 50% of R&D organizations carry out research on nano-scale in nanomaterials, some of them perform in two or even three nano-fields).

At the Russian market we identified 20 nano-companies; about 80% of them played at the nano-material's market. All companies refer to SMEs (mainly spin- offs) also we assume that some companies do not represent themselves like "nano". If compare the Russian Federation to other countries one may observe that Russia has rather strong R&D capacity but is dramatically week in R&D commercialisation and setting up new start-up companies (see Table 1.). Many factors conditioned this situation including historical and cultural; however special part recently played unequal governmental measures: a) there were lack of measures to support spin- offs and start up companies; b) lack of actions to support networks and academia- industry relationships. Russian SIS remains fragmented; there is limited mobility between research institutes and between R&D system and industry. Russian R&D organizations do not have traditions for the commercialization of research results or for the handling of patents and other proper IPR It suffers from a shortage of individuals ready to combine science and business as well as from the weak entrepreneurial tradition (Gaponenko, 2006d).

Table 1. Companies at the market (number)

Regions& countries	Big companies	Daughter companies	Small& start-up	R&D organizations
Asia	50	22	59	111
EU	26	2	125	170
North America	41	41	278	107
Russia*	n. a	n .a	20	266

Sources: *Cientifica and Jakko Poyry Consulting, 2002*
Russia*- companies identified in the project

At the beginning of 2006 two National Programs of Nanotechnology development were launched to focus resources and coordinate the actions and to meet the challenges. In 2007, the President Putin announced that the Government of the Russian Federation would allocate about $7 bill. dollars on nanotechnology development; it is about $2.3bill. per year. However the future trends and impact of nanotechnology on economy and competitiveness of Russian companies depends not only on the budget appropriations but also on how money will be spent, on the building the balanced and adoptive SIS in Nanotech.

Conclusions & Policy

SIS in Nanotech is looking for the trajectories and is marked by diversity and lacking coherence of nano-field in the current embryonic stage. Although nanotechnology are science-driven technologies but to some degree they are pushed by existing industry boarder and are path dependant. At the same time they already drive multidisciplinary and cross-sectoral networks, will change knowledge foundation of NIS, mode of Academy-Industry relations and condition structural shifts in economy.

The private sector plays a special role at the initial stage of SIS formation. First of all it provides a significant contribution to the development of knowledge base for SIS. Although the nano-market is at the initial stage of development corporate R&D expenditures grow faster than the public ones; in some countries they already exceed the budget appropriation on nanotechnology (USA) or are already on the level of public investment in nanotechnology (Asia – Pacific). In addition too, high-tech companies drives collaborations with public R&D organizations and contribute to the multidisciplinary networks emergence and to the formation of new mode of Academy-Industry relations.

Public authorities measures are oriented on the development of information infrastructure, training courses, supporting networks, "filling" institutional gaps in SIS and this way they open the window for private sector.

Emergency of SIS in Nanotech in the Russian Federation shows that cultural issues play a special role at the initial stage of SIS development. One can suggest the following policy recommendations for the Russian Federation: a) to develop measures to support spin- offs and start-up; b) to support multidisciplinary networks, research teams and institutes as well as academia-industry partnership; c) to set up web- site to provide researches and industry by information in nanofield (markets, patents, completed R&D, and the like)**;** d) to support interdisciplinary training and education.

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