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Nanotechnology systems of innovation—An analysis of industry and academia research activities

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Abstract

Nanotechnology promises significant improvements of advanced materials and manufacturing techniques, which are critical for the future competitiveness of national industries. This paper is concerned with the sectoral innovation system in nanotechnology in a global perspective with an aim to understand worldwide developments in nanotechnology research from its emerging stage. The research highlights cross-country comparisons, actors and institutions in the innovation system based on quantitative method (*bibliometrics and tech mining*). The authors present also the varying involvement of academia, public research institutions and commercial companies in relevant research by finding main research contributors, discourse development, as well as clusters or knowledge networks of affiliations and countries. The research findings show that the significant output of commercial companies in Japan and the United States is different from the situation in the European Union, where the relevant scientific activities are dominated by academic and government research institutions. The research reveals the learning patterns of nanotech innovation structure for the science pole. The findings can be particularly useful for forming technology strategies, science and technology policies by revealing strengths and weaknesses of the emerging innovation system in nanotech, existing country-level competencies and differences.

Keywords: Nanotechnology; Innovation system; Bibliometrics and tech mining; Nanotechnology research; Science and technology policy

1. Introduction

Nanotechnology has been regarded as an emerging technology, introducing new dimensions to science and technology with the possibility of manipulating atoms and molecules at the nanometer level ('nano' means one-billionth of a meter). This emerging technology has multiple possible applications and thus affects various technological domains including advanced materials, biotechnology and pharmacy, electronics, scientific tools and industrial manufacturing processes. In the early stage of nanotechnology development and diffusion, many expected benefits have not yet been fully accomplished. However, scientists and researchers in the scientific disciplines aggressively got involved in the relevant research as a parallel way to boost nanotech competitiveness through academic research, and corporations have been directing their R&D activities towards the exploration of nanotech opportunities. From the scientific point of view, "Nanotechnology can be defined as referring to materials and systems with structures and components exhibiting novel and significantly improved physical, chemical and biological properties, as well as to the phenomena and processes enabled by the ability to control the material properties on the nano-scale size" (NSTC, 2002).

The emergence of nanotech was enabled by the development of specialist instruments, which in turn facilitated the observation and manipulation of nanostructures at the atomic or molecular scale, as well as the discoveries of new nanomaterials such as fullerenes and carbon nanotubes[1]

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[1] *Fullerenes* called carbon 60, a new class of carbon material, are spherical molecules about 1 nm in diameter, comprising 60 carbon atoms arranged as 20 hexagons and 12 pentagons: the configuration of a football. *Carbon nanotubes (CNTs)* are extended tubes of rolled grapheme sheets, single-walled and multi-walled types. CNTs have assumed an important role in the context of nanomaterials, because of their novel chemical, physical and electrical properties. They are mechanically very strong as stiff as diamond, flexible about their axis and can conduct electricity extremely well. All of these remarkable properties give CNTs a range of

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(which offered a foundation for creating nanoproducts with enhanced performance parameters of electronic, cosmetic, textile and other industries). Nanotech offered also new opportunities in rapid development of miniaturization techniques (so-called 'top-down' approach, involving decomposition into the smallest manageable entities) and building macrostructures (so-called 'bottom-up' approach, allowing re-engineer materials at nanolevel and using them in developing new and improved products).

The study interprets the scientific development of nanotech using the framework of systems of innovation (Carlsson et al., 2002, Malerba, 2002), denoting a network of actors and institutions in the public and private sectors, developing and diffusing innovative technologies. The framework is applicable on several levels (Carlsson et al., 2002)—systems of innovation can be national, regional, sectoral, or related to a specific technology which has an impact on various industries (as in the case of nanotech). It interprets the innovation as a dynamic process, involving multiple interacting and co-operating actors, changes in the underlying technologies, society and business models (Carlsson et al., 2002).

A useful method of structuring and interpreting the roles and linkages within a technological system is provided by the framework of techno-economic network (Bell and Callon, 1994), introducing a concept based on financial, market, regulatory, technology and science poles (practical applications of the framework to selected industries, e.g. Kumaresan and Miyazaki, 1999 on robotics; Klincewicz and Miyazaki, 2005 on software industry). The present research focuses on the science pole, where academic publications are regarded as viable scientific output indicators—an analysis in line with recommendations of the technology mining method (Porter and Cunningham, 2005) that can reveal additional important facts, related to academia, public research institutions, commercial companies and help forecast further technological developments.

2. An overview of nanoscience and nanotechnology

2.1. Distinctive features of nanoscience and nanotechnology

Nanoscience and Nanotechnology are widely seen as having huge potential to many areas of scientific research (such as physics, chemistry, material sciences, biology, engineering) and technological applications (such as healthcare and life sciences, energy and environment, electronics, communications and computing, manufacturing & materials) because of its nano-scale where the materials' properties are significantly different from those of the same materials in bulk or macroscopic form. Although there is no sharp distinction between them, 'nanoscience' is concerned with understanding some phenomena (such as surface tension/properties, quantum effects, molecular assembly) and their influence on the properties of material, whereas 'nanotechnology' aim to exploit these effects to create structures, devices and systems with novel and significantly improved properties and functions due to their size (RS and RAE report, 2004). Therefore, nanotechnology encompasses the work of nanoscale science, increased understandings of interactions in the atomic or molecular scale and the capability to characterize and control materials using nano-tools. Nanotechnology, which is both scientific and technical (Kearnes report), is fundamentally about making things (i.e. the construction, generation and growth of objects, devices and architecture). Since the concept and meaning of nanoscience and nanotechnology is wide ranging, the only feature in common is their nano-dimension or scale by which it operates. We found the term 'nanotechnology' to be more appropriate instead of using both terms which may lead to some confusion.

2.2. Diversity of nanotechnology

Nanotechnology has a multidisciplinary character, affecting multiple traditional technologies, scientific disciplines and industries. Additionally, through the nanotech revolution, boundaries between previously distinctive disciplines such as mechanics and chemistry begin to blur, stimulating knowledge transfer and cross-fertilization (Nicolau, 2004). Many scientists believe that nanomaterials will induce a new generation of consumer products, based on miniaturized computer chips, nanoscale sensors, and devices for sorting DNA molecules, integrating microsystems and biotechnology (Ikezawa, 2001).

Nanotechnology innovation can be characterized as evolutionary from micro to nano. An important feature of nanotech is that it is not restricted to the realm of advanced materials, extending also to manufacturing processes, biotechnology and pharmacy, electronics and IT, as well as other technologies. Table 1 shows relevant examples of nanotech impacts and possible applications in various technology realms.[2] In the advanced materials realm, nanomaterials [three categories exist based on structural shape: (i) materials that have one dimension in nanoscale are layers, such as thin films or surface coatings with length; (ii) materials that are nanoscale in two dimensions include nanowires and nanotubes with length and width; (iii) materials that are nanoscale in three dimensions are particles, for example colloids and quantum dots with length, width and depth] are going to transform medicine and medical instruments, electric devices, energy sector, cosmetics, and chemical materials. Disease diagnosis, drug and gene therapies are likely to be affected in

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(*footnote continued*)
potential applications: for example, in reinforced composites, sensors, nanoelectronics and display devices, etc.

[2] The areas of applications were categorized on the basis of a report published by The Royal Society and the Royal Academy of Engineering on "Nanoscience and Nanotechnologies: opportunities and uncertainties" (2004).

Table 1
Nanotechnology applications in various technology realms

Categories	Examples of Materials	Examples of Applications
I. Applications in the advanced materials realms		
One dimensional nanomaterials	Thin films and layers	Breathable and waterproof fabrics, electronic devices, vehicles
	Engineered surfaces	Fuel cells, catalysts
Two dimensional nanomaterials	Carbon nanotubes	Reinforced composites, antistatic packaging, sensors, nanoelectronics, display devices
	Inorganic nanotubes	Catalysis, photo-catalysis, energy storage
	Semiconductor nanowires	High-density data storage, electronic and opto-electronic nanodevices, quantum devices
Three dimensional nanomaterials	Nanoparticles	Sunscreens, cosmetics, textiles, aircraft paint coatings, targeted drug delivery, catalysts, water remediation, car bumpers and tyres
	Nanocrystalline materials	Magnetic resonance imaging (MRI), motors, microsensors, orthopaedic implants, artificial heart valves
	Fullerenes (spherical C_{60} carbon materials)	Ball bearings to lubricate surfaces, drug delivery vehicles, electronic circuits
	Dendrimers (spherical polymeric molecules)	Nanoscale carrier molecules in drug delivery, environmental clean-up, coatings, inks
	Quantum dots (nanoparticles of semiconductors)	Solar cells, composites, fluorescent biological labels
II. Applications in the biotechnology and Pharmacy realm		
Bio-mimetic structures	Catenanes and rotaxanes	Disease diagnosis, drug delivery, molecular imaging
	Nanocrystalline silver	Wound dressing
Array technologies	DNA chip	Gene and protein analysis
	Lab-on-a-chip	Sensing and supporting disease diagnosis
Self-assembly	DNA-based structure (artificial crystals)	Hybrid nanomachine
Drug delivery	Functionalized nanoparticle (polymer conjugates)	Drug therapies, gene therapies, cystic fibrosis and immune deficiencies
III. Applications in the electronics and IT realm		
Information storage	Low dielectrics and higher-conductivity interconnects (wiring)	DRAM for digital camera, personal computer, video camera etc.
	Semiconductor nanowires	Hard disk drive for PC, DVD player, CD player
Optoelectronics	Photonic crystals	Displays, optical sensing, optical computing
	Optical devices (nanowires)	Point-of-care health screening, constant monitoring of diabetes or critical care
Sensors	Nanocrystalline materials with increasing selectivity	Monitoring the quality of drinking water, state and performance of products and materials, detecting and tracking pollutants, checking food for edibility

Source: The authors' design.

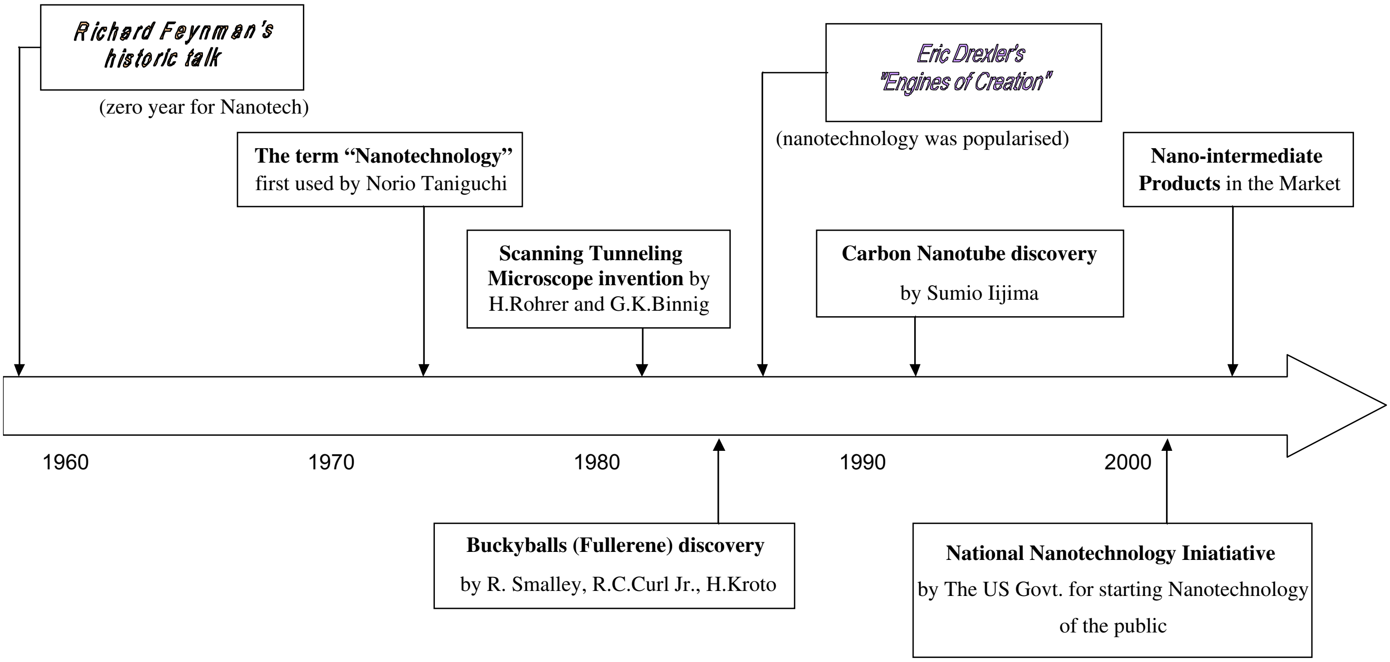

Fig. 1. Pathway of major nanotechnology discoveries.

the biotechnology and pharmacy realm. Finally, nanotechnology is also expected to bring about profound changes to the consumer electronics area thanks to its innovative applications in electronics and IT realm.

2.3. *A brief history of nanotechnology*

The history of nanotechnology began in 1959, when Richard Feynman (a physicist of the California Institute of Technology), in his famous lecture "There is Plenty of Room at the Bottom", proposed the concept of nanotechnology. It suggested that the frontiers of knowledge and technology at which people should be aiming could be found not only in physics, but also in nano-sized fields. In the 1980s, the invention of the scanning tunneling microscope (STM), a computer imaging system with a surface probe, enabled the manipulation of atoms and molecules, by which most significant change has been brought in this field. Since then, developments in nanotech continued with significant discoveries of nanomaterials such as fullerenes and carbon nanotubes. A pathway of major nanotechnology discoveries is presented in Fig. 1.

An important revolution in analytical instruments, preceding discoveries and subsequent technological advancement (Rosenberg, 1982), stimulated the exploration of nanoscale structures and the developments of nanoscale technologies. It has been estimated that nanotechnology is currently at a level of development similar to early commercial applications of information technology in the late 1960s or to the emergence of biotechnology in the 1980s (Roco, 2005), and further impressive discoveries, transforming the affected technological domains, are to be expected.

3. Research problem and method

The main objective of this paper is to analyze the past developments and current status of nanotech research worldwide. Previous studies include Meyer's (2001) analysis based on SCI database, which included 5400 nanotech-related papers focusing on the period of the 1990s, revealing S–T linkage between patents and publications; Hullmann and Meyer's study (2003) with SCI papers from 1981 to 1998, delineating nanotech from the so-called nanoscience (encompassing scientific disciplines affected by the nanotech revolution, but pursuing mostly basic research); and recently Leydesdorff and Zhou (2006) with an analysis of China's performance in nanotech, focused on journal-journal citation relations. Other recent studies related to nanotech by Bhat (2005), Wonglimpiyarat (2005) and Hung and Chu (2006). It can be argued that thanks to new scientific discoveries and commercial developments, these boundaries are blurred nowadays, and science and technology researchers and policy makers could greatly benefit from a re-examination of the status of the entire domain of nanotech in the mid-2000s.

This analysis is based on relevant scientific outputs in a global perspective—nanotech-related academic publications from Elsevier COMPENDEX database in a 15-year time- frame (1990–2004); starting with first relevant academic articles and tracking almost the entire lifecycle of the technology evolution. Altogether 28,559 nanotech-related articles were retrieved through queries; based on 175 specialist keywords,[3] derived from the nano science

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[3] The keywords included among others: nanomaterial, nanoparticle, nanocrystal, nanocomposite, carcon nanotubes, fullerenes, nanoscale,

and technology institute (NSTI) publications. The subsequent analysis was performed using a dedicated tech mining software vantage point, automating mining and clustering of terms occurring in article abstracts and article descriptors such as authors; affiliations or keywords.

The article attempts to answer a fundamental question: (i) What type of organizations are most active in scientific and engineering research related to nanotech (what are the top countries, top institutions, top authors in the relevant research and what is the science profile of advanced countries related to nanotech)? The authors attempt to identify key countries and actors in nanotech research activities, and how it has changed by scientific output over time. The research involves cross-country comparisons, but at the same time looks at Asian as well as Western countries, trying to identify similarities and potential for international co-operation, especially when contrasting the Asian output with contributions from the EU and the United States.

Apart from scientific output measures and quantitative assessment, the authors also attempt to identify distinctive scientific profiles of individual countries, analyzing their particular research interests and knowledge networks of nanotech practitioners. Similar studies were conducted on robotics (Kumaresan and Miyazaki, 1999) and software industry (Klincewicz and Miyazaki, 2005). Other relevant works on innovation system include Lastres (1994) who studied the Japanese system of innovation in advanced materials. The study applies tech mining methodology, proposed by Porter and Cunningham (2005), combining bibliometrics with text mining and quantitative study. Tech mining analyzes relations between actors and technologies within a given innovation system, based on input data from article or patent databases.

The following research was based on an article set extracted from Elsevier COMPENDEX database, one of the most representative collections of peer-reviewed scientific and technical articles, aggregates article abstracts from the leading science and engineering journals (among others: Journal of Physical Chemistry, Langmuir, Synthetic Metals, Advanced Materials, JACS, Nanotechnology, Fullerene Science and Technology, IEEE Transactions on Nanotechnology etc.), not only journals published by Elsevier as well as proceedings of the International Society for Optical Engineering and the Materials Research Society Symposium, etc. The authors found the mere use of prefix "nano-" of previous studies (Meyer, 2001; Hullmann and Maeyer, 2003) as too restrictive and not encompassing many relevant nanotechnological categories.

The broad spectrum of nanotech and the use of 175 keywords instead of the prefix "nano-" offer an opportunity to better capture the relevant developments. In addition, the authors used specialist tech mining software vantage point, which goes beyond limitations of traditional, paper-based bibliometric research, usually involving simple but not always reliable techniques such as co-word analysis—the use of specialist computer software helps us to statistically and textually analyze articles, cluster thousands of keywords or specialist terms occurring in abstracts, thus increasing the reliability of the findings and opening up new analytical opportunities. The article abstracts from the database imported to vantage point, which removed duplicates or empty records, and facilitated the subsequent analyses.

4. Cross-country comparisons of Asia and Western regions

Nanotechnology is highly prioritized on the global scientific agenda. Many Asian and European countries regard it as an interesting area of future exploitation, setting up national initiatives in order to prepare for the technological challenge. Volumes of scientific publications are a commonly accepted indicator of scientific performance in specific technological domains—they help illustrate the existing status and forecast future developments of a technology. Table 2 shows the key trends and the respective involvement of Asian countries including Japan, EU and the United States in scientific & engineering research related to nanotech. Asian countries accounted for approximately 40% of global scientific nanotechnology-related output over the period of 1990–2004. As Table 2 reveals, the article volumes enjoyed a strong growth since the early 2000s, proportionally increasing the Asian output in nanotech research illustrated in Fig. 2. It can also be demonstrated that the United States was falling behind European Union in the late 1990s, but leads the pack in the early 2000s, simply because the US government

Table 2
Overall volumes of scientific output over time related to nanotech

Total share by worldwide	Time frame	Total number by region			
		7197 European Union	7169 United States	9696 Asia	3977 Japan
2	1990	1	1	0	0
1	1991	0	1	0	0
18	1992	2	5	5	5
19	1993	7	2	6	4
285	1994	69	112	61	37
1050	1995	269	307	325	181
1171	1996	422	246	374	214
1350	1997	415	275	440	226
1140	1998	348	230	372	165
1580	1999	502	294	555	279
1789	2000	534	381	614	269
2602	2001	685	593	905	362
3676	2002	919	926	1247	539
5318	2003	1216	1430	1839	652
8558	2004	1808	2366	2953	1044

(*footnote continued*)
nanotubes, nanostructures, nanofiber, plastic nanocomposites, strain-resistant fabrics, nanocoating, nanofilms, nanostructures thin films, nanorobotics, quantum dot lasers, nanosensor, biological nanosensor, targeted nano-therapeutics, etc.

announced nanotechnology for the public by establishing national nanotechnology initiatives (NNI) and the rest of the world followed them.

Shares of individual Asian countries in nanotech research vary, with particularly strong positions of Japan and China. Japan accounts for 42% of Asian players and China (including Hong Kong) 31% of nano-related publications, with its basic comparisons worldwide as Fig. 4 demonstrates. The volumes of nanotech-related articles in Japan are slowly increasing from 1994 to 2002 and experience a dynamic uptake in 2003 and 2004. China (including Hong Kong) saw a rapid increase in 2002–2004 to catch-up with Japan by the end of the period (Fig. 3). In Asia, Japan holds its strong share from the beginning up to the early 2000s and then loses its position (2003–2004) because of new entrants such as China. On the other hand, South Korea, Taiwan and Singapore demonstrate comparatively slower advances. Shares of individual countries in EU also varied with particularly strong position of Germany, France, UK and Italy. Very slow advances observed in nanotech research by other EU countries, illustrated in Fig. 5.

Specific circumstances of different countries, such as rates and levels of economic development, levels of education of the workforce, as well as specific industrial strengths and weaknesses, induce the differentiation in science and technology policies of countries, attempting to gain and maintain the leading edge in nanotechnology (Nicolau, 2004). For example, the government of Singapore has been backing nanotechnology research in the areas of high density data storage, highly integrated chips and biomedical applications (Wonglimpiyarat, 2005). These specific initiatives have an impact on scientific output related to nanotech. Taiwan and South Korea are

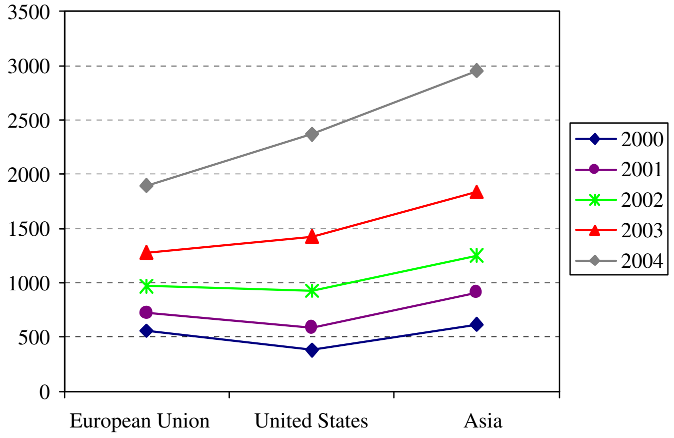

Fig. 2. Comparative regional output over the period 2000–2004.

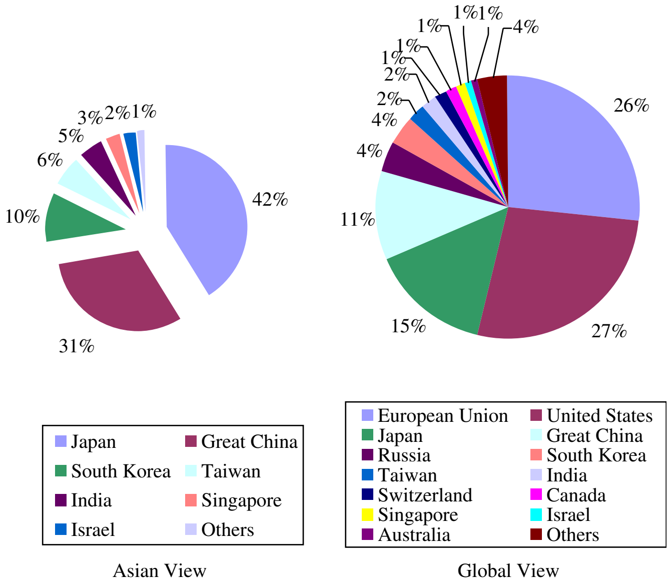

Fig. 4. Shares of Asian players and global leaders in nanotech related publishing.

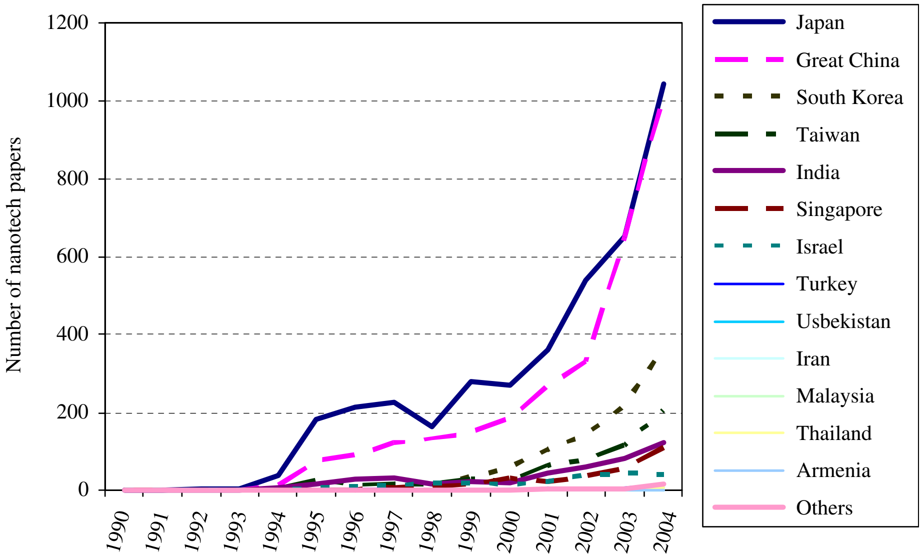

Fig. 3. Asian nanotech article volumes comparison over time (1990–2004).

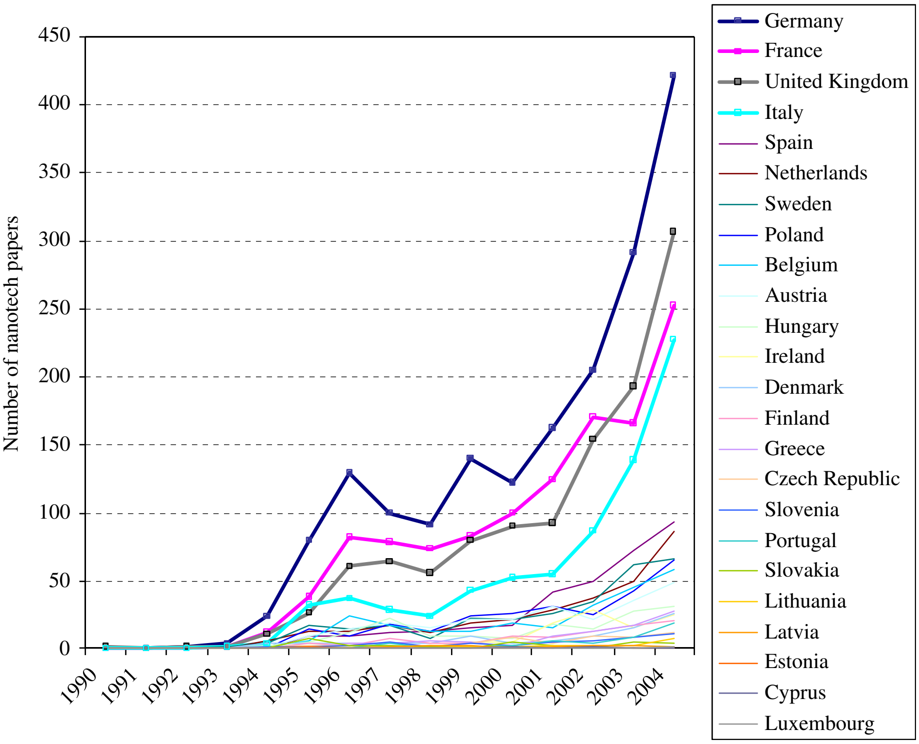

Fig. 5. EU nanotech article volumes comparison over time (1990–2004).

in turn pushing nanotech R&D related to nanomaterials and electronics, particularly computer memories and logic devices—the government policy is supportive to large numbers of commercial companies, engaged in the R&D of nano-related products in semiconductors, integrated circuits, flat panel displays, optoelectronics and electronics appliances. In China (including Hong Kong), its nanotech policy strongly emphasizes the establishment of national R&D laboratories and industrial parks-these top-down initiatives helped China catch up with Japan in 2004, as demonstrated by Fig. 3.

Compared with other countries in Asia, Japan is gradually losing its lead, measured by the share of scientific nanotech publications (it should however be noted that the position on the science pole of the techno-economic network cannot merely be measured by number of publications, but also their importance for researchers and practitioners—citations and commercial impacts—and additionally by aggregate national R&D expenditures on an emerging technology). In spite of the decrease of Japan's relative share in Asia in 2003–2004, the article volumes are constantly growing, but the dynamics is slower than in other countries such as China, posing nowadays a significant competitive threat to the established R&D leader in the region. This type of specialty is not visible in the EU countries case, where each country shows their continuity in nanotech research by high growth countries such as Germany, France, UK, Italy and low growth countries (rest of them).

It is better to compare on a relative rather than an absolute basis. We therefore converted the data to relative advantages. The transformation widely adopted in recent work on comparative technological development at both country and sector level is the Revealed Technological Advantage (e.g. Cantwell, 1993). To view a comparative dynamics, we compared EU, the US, Japan and China (including Hong Kong) which are the most advanced players in nanotech (similar studies done by Kumaresan and Miyazaki on robotics). Miyazaki (1995) conducted a study on optoelectronics-related competence building in European & Japanese firms using a similar approach. The dynamic changes in the comparative positions of different countries are identified by a tool introduced by Patel and Pavitt (1997) for categorizing the technological competencies of firms in the Science and Technology poles. The *X*-axis in the Science pole represents the share of publication activities and *Y*-axis indicates the revealed technology advantage (RTA) of the countries to measure the comparative advantage of the technological strength.

A value above 1 indicates relative strength and a value less than 1 indicates relative weakness. The regions of high share and high RTA can be interpreted as countries having relatively more share in the Science pole (i.e. relative importance to competencies in nanotech) and having distinctive advantage nationally in nanotechnology.[4] Similarly the region of low share and low RTA reveals

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[4] The RTA-index has been used as an approximation of the advantages in certain technology fields, consists of the ratio of the number of patents of a country in a particular technological subdomain, divided by the total number of patents in this subdomain, and the number of patents of the country under study in the whole field, divided by the total number of patents in the field RTA $= (P_{ij}/\Sigma_i P_{ij})/(\Sigma_j P_{ij}/\Sigma_{ij} P_{ij})$; The firm's RTA in each

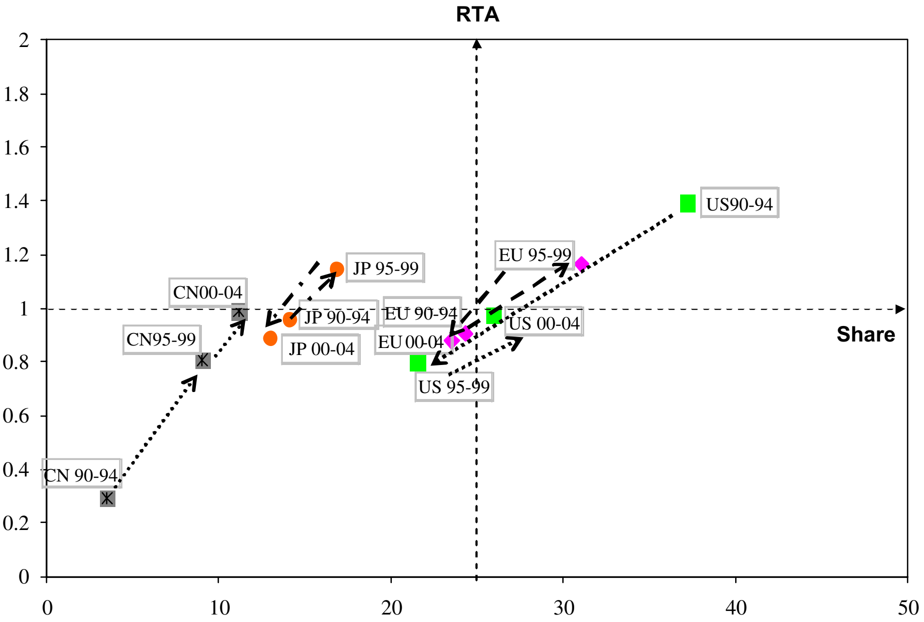

Fig. 6. Science profile of advanced countries in nanotech research.

countries allocating relatively less resources to nanotech and having less distinctive advantage nationally. It is to be noted that the value of the benchmark share in the *X*-axis is difficult to identify and varies depending on various dimensions such as the countries or region considered, innovation process analyzed, national requirements etc. In this case, a break-even share is chosen in order to accommodate all countries in such a way that a proper comparison of their innovation system can be made. Therefore, in this analysis, what matters is the direction of movement and comparative positions rather than absolute positions.

Fig. 6 demonstrates that the Japanese position in the Science pole moved from a low share and low RTA zone towards a high share and high RTA zone in mid 1990s. The Japanese contribution in nanotech research was less in the early 1990s and then it slowly picked up to around 17% in 1995–1999 and 13% in 2000–2004. The RTA was less than 1 in the early 1990s and then it rose to 1.14 in 1995–1999 and again dropped to 0.88 in 2000–2004. This indicates that relative to other domains, the nanotech research system in Japan has been gaining strength in mid 1990s and falling behind in recent years. Similar approach was observed in the case of EU. On the other hand, the US trajectory is moving in the opposite direction to Japan and EU. It has been losing both its relatively higher share and RTA in nanotech research in mid 1990s. The decline in RTA may due to entry of many other countries into nanotech basic research activities. However, picked up its position again in the early 2000s, which may due to the US government announced to push nanotech by establishing NNI in the early 2000s. While China (including Hong Kong) contributes relatively low percentage share than other countries in the Science pole, its distinctive advantage in nanotech is still low (RTA is less than 1), but promising in future. The direction of Japan and EU are approximately the same in the Science pole and the direction of the US is opposite to that of Japan. The analysis reveals the learning patterns of innovation structure for the Science pole in a comparative evolutionary perspective.

5. Actors and their activities in nanotechnology research

Emerging technologies are often developed thanks to the initial strong involvement of publicly-funded research institutions, which gradually encourages commercial companies to engage in applied research and development of specific applications. The present research differentiates universities, public research institutes and private companies—the analysis follows therefore the triple helix model, contrasting the roles of academia, government and industry. It should be noted that in the Asian context, many academic institutions are also directly publicly funded as opposed to the US higher education system, where the distinctions between public research institutes and universities are blurring.

5.1. Role of university and public research institutes

As the present research revealed, universities have particularly large shares in nanotech research (they account for 70.45% of nanotech-related research worldwide), and public research institutes complement them (with 22.22% share of articles)—this is not surprising due to the emerging status of nanotech and the significance of basic research

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(*footnote continued*)
technological fields is similar to the *revealed scientific advantage* (RSA) measure used to assess the scientific performance of countries.

(Table 3). Private sector plays a more limited role (globally 7.33% of articles), but is prominent in the United States (12.41%). In Asia, Japan holds a strong share (12.30%) in the private sector, South Korea (8.25%) competing Japan and to a lesser extent India (3.52%), helping advance nanotech, as illustrated by Fig. 7—companies in these countries have effectively exploited the earlier publicly funded research efforts to generate first commercial applications. In other Asian countries, the involvement of private companies is less active, and national innovation systems related to nanotechnology continue to rely on contributions by universities and government labs. Fig. 8 demonstrates the European Union case, where private sector involvement is quite strong in Germany, France, Netherlands, Italy and Switzerland, whereas Hungary and Poland have no private sector involvement. The other EU

Table 3
Shares of nanotech research by actors over time (1990–2004)

Total by region	Region	Total by affiliation					
		University		Public Research Institute		Industry	
		Total 18944	% Share 70.45	Total 5973	% Share 22.22	Total 1970	% Share 7.33
7197	European Union	5089	70.71	1711	23.77	395	5.49
7169	United States	5276	73.59	1006	14.03	890	12.41
9728	Asia	7071	72.69	2044	21.01	613	6.30

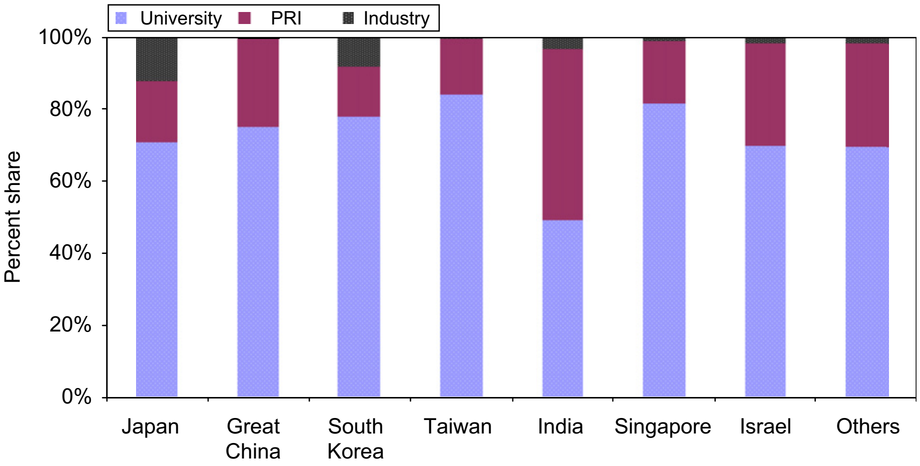

Fig. 7. Comparisons of Asian institutions' role in nano-scientific development.

Fig. 8. Comparisons of EU institutions' role in nano-scientific development.

countries' nanotech research is dependent on universities, except Russia where public research institutes contribute significantly in their scientific development in nanotech.

The activities of the actors in the Science pole (percentage of activities of university and public research institute, compared with other actor groups) showed signs of improvements. From the early introduction, universities played a major role in nanotechnological research activities, and private companies played a limited role. The number of scientific papers produced by universities globally had reached 18 944 (70.45% of total), of which 7071 (41%) were from Asia, 5276 (30%) from American universities and 5089 (29%) from the European Union. Public research institutes contributed 5973 (22.22% of total), of which 43% come from Asian region, 36% from EU by competing with Asia and 21% from the US public research institutions, as illustrated by Fig. 9. List of top

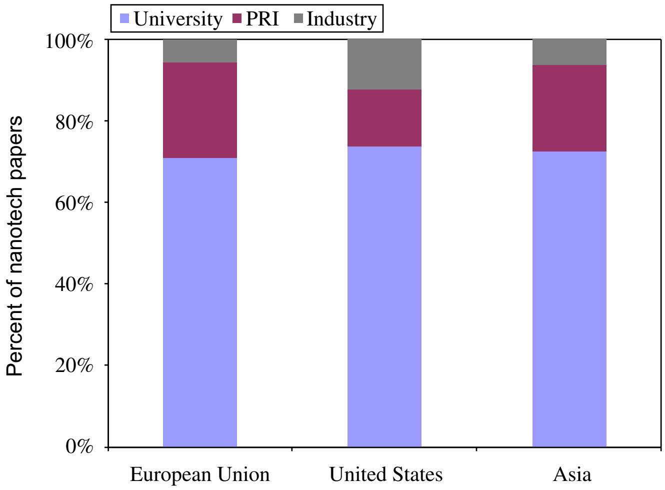

Fig. 9. Actor structure in the Science pole.

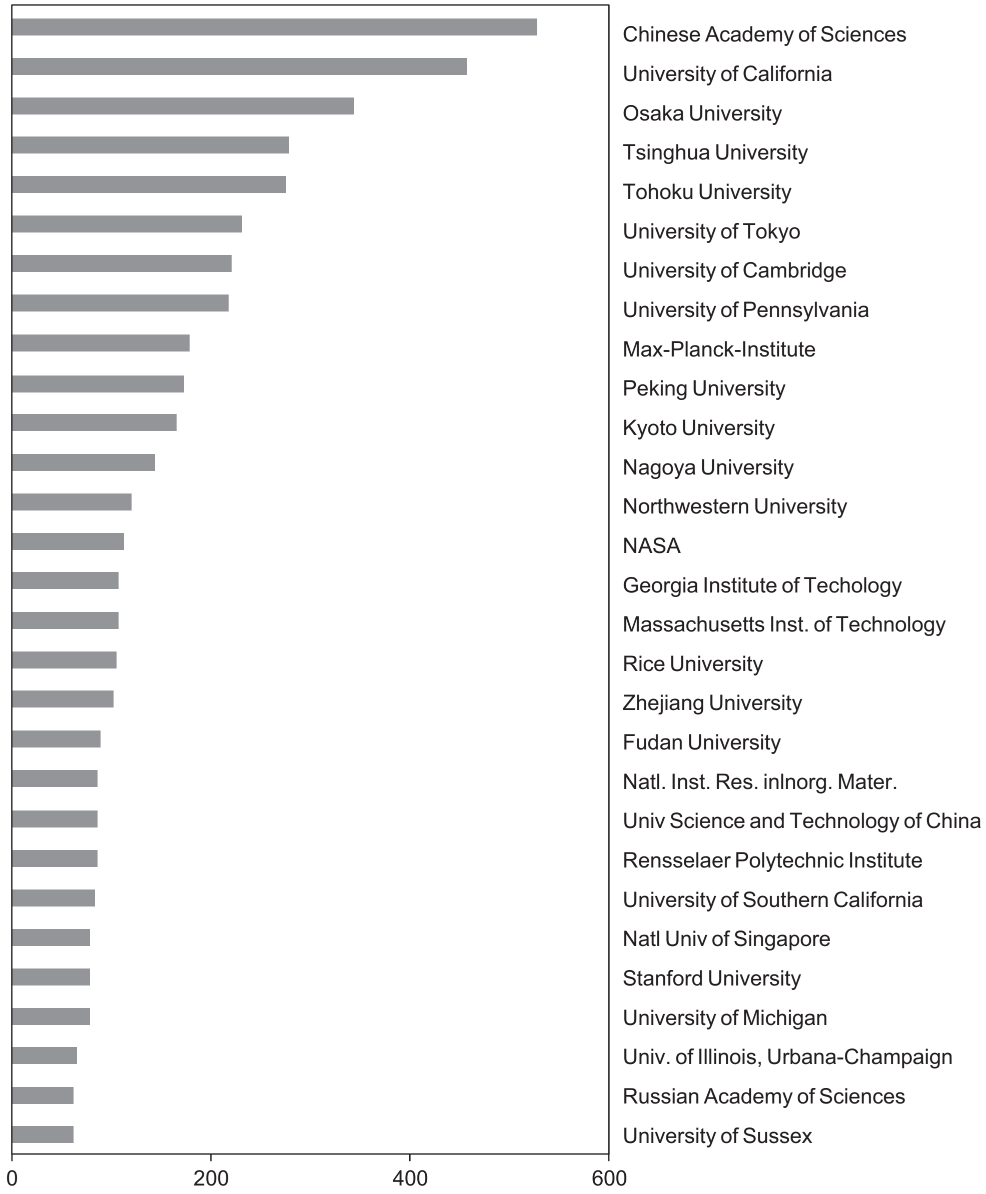

Fig. 10. Most active universities and PRI in nanotech research.

affiliations worldwide (universities and PRI) are demonstrated in Fig. 10, where institutions from Asian origin and the United States provide a significant role in nanotech scientific developments. Japanese and Chinese Institutions are mainly involved in the top order except University of California from the United States, University of Cambridge from UK and Max-Planck Institute from Germany.

5.2. *Role of private sectors*

The number of scientific output produced by private sectors reached 1970 (7.33% of all articles), of which the United States hold 890 (47%), 613 (32%) from Asian region and 395 (21%) from European Union (Table 3). It is worth remarking that Japanese private sector's role is extremely significant in Asia. Contribution from Japan to scientific developments is 80%, only South Korean Samsung fill up the gaps among other countries activities within this sector. Table 4 lists the most active companies generating scientific nanotech research, showing all commercial organizations with at least 10 relevant publications in the analyzed 15 years time frame (1990–2004). It reveals an important role of Asian (particularly Japanese) and US companies in privately-funded basic research worldwide.

Table 4
Private sectors' nanotech research output over time (1990–2004)

Number of publications	Name of companies	Country of origin
120	NTT Corporation	Japan
110	IBM	United States, Swiss, Japan, Germany, Israel
69	Samsung	South Korea, Germany
62	NEC Corporation	Japan, Germany
58	BELL Laboratories	United States
41	SUNY	United States
35	Motorola	United States, France
35	Philips	Netherlands, Germany, South Korea
33	Infineon Technologies	Germany, United States
29	Sony Corporation	Japan
29	Toshiba Corporation	Japan
26	Sumitomo Group	Japan
22	Hitachi	Japan, United States, UK
21	TOYOTA	Japan
20	Intel Corporation	United States
18	Ultratech Stepper	United States
18	Progega	Italy
18	Xerox	United States, Canada
17	Hewlett-Packard	United States
16	SPINTEC	France
16	Fujitsu	Japan
14	Seashell Technology	United States
12	Xilinx Inc.	United States
12	Nikon Co	Japan, UK
12	Texas instruments	United States, India
11	Zyvex	United States
10	Seagate Technology	United States
10	Nanomix	United States
10	Semiconductor Research Corp.	United States
10	Sincrotrone Trieste	Italy

Asian companies active in nano-related research, encompass many different industries. The research leader NTT, is a telecom operator, building absorptive capacities through basic research, not using the research findings directly in product development, but rather to co-ordinate supplier networks and set directions for their activities. NEC, Samsung, Sony, Toshiba and Hitachi are electronics companies, potentially using nanotech knowledge in development of various product families, particularly semiconductors and displays. Sumitomo groups focuse hoping on chemical and electric applications, while Toyota is active in automobile market, hopes to capitalize on nanomaterials incorporated in next generation products, and Nikon pursues research relevant to high-precision photographic equipment. The US based private companies are mostly electronics companies as illustrated in Table 4, potentially developing various electrical product families, particularly semiconductors.

6. Nanotechnology research focus and knowledge network

Vantage Point software uses clustering and cross-correlation techniques to compare analyzed objects (countries or organizations) by measuring and visualizing the similarity of their focus. The computer-generated map (Fig. 11) uses physical distance to symbolize the proximity or divergence of academic focus. In the present study, the measure is based on a computer-supported analysis of 49,282 keywords, which were supplied by article authors to classify the analyzed article set. Each article was associated with multiple keywords, and vantage point identified relevant keyword clusters, revealing similarities in research interests of specific countries.

The size of a circle, symbolizing the respective country, indicates the overall volumes of articles written by the authors with a particular national affiliation. Lines linking specific countries symbolize statistically hypothesized relations between the analyzed objects (degrees of similarity). Tech mining methodology helps reveal hidden variables and relations in the analyzed data set—for example, similar research interests of academics and firms from the same geographical area would not necessarily be a mere coincidence (Porter and Cunningham, 2005). This identification of hidden linkages is particularly important in the Asian context (compare findings about Asian software industry in Klincewicz and Miyazaki, 2005). Researchers analyzing Japanese universities suggested that even though many schools did not have institutionalized cooperation programs with industrial companies, individual professors used to work closely or be affiliated with specific firms, and these informal cooperation patterns affected the focus of academic research, stimulating spillover-like technology transfers (Kodama and Branscomb, 1999).

On the cross-correlations map, one can identify strong links between certain areas of nanotech research in Japan and Taiwan; China with Taiwan and India; Taiwan with South

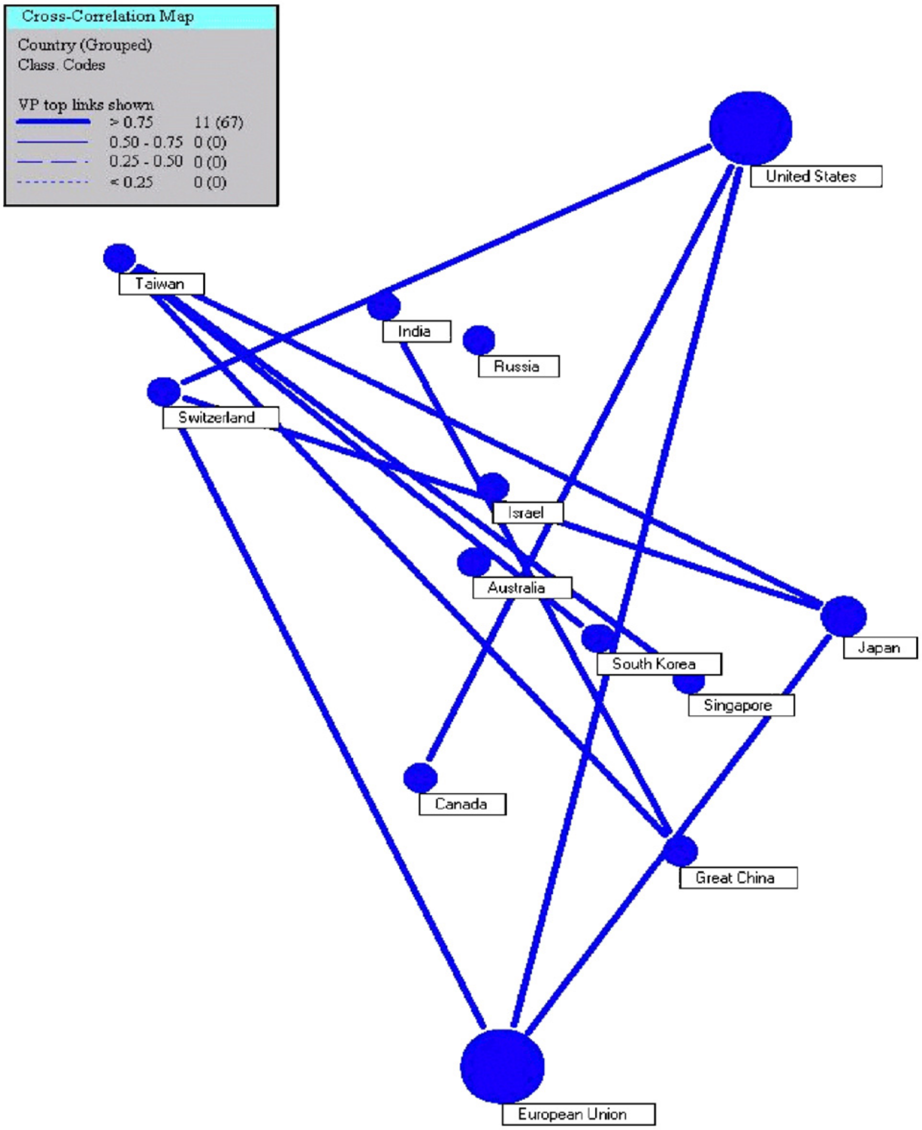

Fig. 11. Cross-correlation map presenting research focus of the analyzed countries (1990–2004) (*Image generated by Vantage Point*).

Korea and Singapore suggesting the existence of, or the potential for a closer cross-border academic co-operation, as research teams from the concerned countries seem to adopt similar approaches to certain problems. The co-operation could be particularly fruitful, if the research areas of both countries are relatively different (as indicated by the physical distance on the map), and therefore could complement each other, thanks to the use of similar research orientations. At the same time, the lack of such a linkage between South Korea and Japan, or between Singapore and Japan, situated closely on the cross-correlations map, can be interpreted as the convergence of research interests, but the divergence of research approaches. As the map indicates, the United States and EU differ significantly from other countries because of the scale of nanotech activities and long research experiences. For Japan, the map suggests a potential for co-operation with EU, rather than the United States.

As the research findings reveal, universities dominate nanotech research, and public research institutes play important roles in complementing them. Most of the nanoscientific research comes out from university researchers. Vantage Point software uses clustering to generate images of a specific class or an individual activity. Fig. 12 illustrates the cluster of knowledge network of top authors in scientific research. It reflects the network of researchers' interest such as in electronics sector (plasma display: basically South Korean researchers; solar cells: European researchers), in nano-instrumentation sector (TEM & STM: it combines European and Asian experts), and especially in chemical synthesis (contribution from Chinese researchers). All the researchers' activity is based on nanostructured materials of carbon nanotubes and fullerene.

Table 5 lists the most productive nano-researchers' frequency of article volumes, affiliations involved and the time frame of their research publications from worldwide

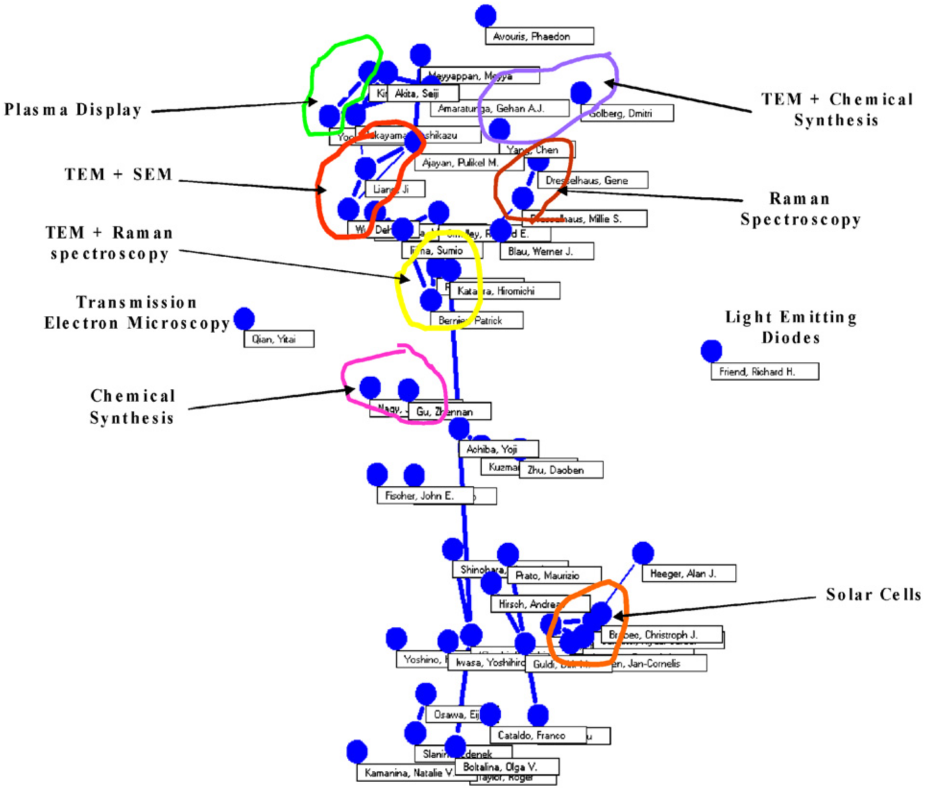

Fig. 12. Knowledge network of top researchers in nanotechnology (*Image generated by Vantage Point*).

(i.e. co-authoring the largest numbers of scientific articles)—it has to be emphasized that a researcher's productivity does not necessarily correspond to significance of his findings or impact factor, and captures quantity not quality of scientific work, but incidentally, the table includes some of the most significant nanotech researchers and their contribution in nanotech coming out from the mid 1990s.

The presented findings have important limitations, as they are merely based on large-scale statistical profiling, using article keywords (provided by authors). When making science and technology policy decisions, conclusions from aggregate studies should always be contrasted with individual analyzes, based on a better understanding of specific research areas and topics in the concerned countries. Possible research bias may result from the fact that keywords in COMPENDEX are either assigned by article authors or COMPENDEX librarians, but there is no universal thesaurus or categorization scheme. For emerging technologies, the scheme should additionally be refined post hoc—many important scientific terms (e.g. carbon nanotubes) were initially not regarded as established keyword terms, and the first relevant articles were classified using other categories

7. Discussions and policy implications

The research showed that Asian countries play an important role in the global nanotechnology research, accounting for approximately 40% of all scientific and technical articles worldwide. It demonstrated the dominant position of Japan and catching up processes of China in Asia; similarly Germany, France, UK and Italy in EU; which are becoming major players in this emerging technology area. Detailed analyzes of national focus help identify strengths and weaknesses, illustrate the existing status and forecast future developments of nanotechnology, useful for science and technology policy makers. The research analyses pointed to the existence of strong links between research orientations of specific countries, suggesting the potential for a closer cross-border scientific co-operation.

The policy makers can benefit from the findings of competitive and comparative nanotechnological research output of individual Asian and European Union countries as well as of the United States. In Asia, the top-down initiatives for nanotech (establishment of national R&D laboratories and industrial parks) of mainland China (including Hong Kong), helped them to catch up Japan in 2004, demonstrated clearly by this research findings. Compared with other countries in Asia, Japan is gradually losing its lead (simply because of new entrants), measured by the share of scientific nanotech publications. However, the article volumes are constantly growing, but the dynamics is slower than in other countries such as China, posing nowadays significant competitive threats to the established R&D leader in the region. While in the EU, each player has been continuously increasing its nanotech research effort as seen by the case of Germany, France, UK and Italy. Consequently the United States has maintained its strong position from the beginning.

Table 5
Lists of most productive nanotech researchers worldwide over time (1990–2004)

Name of authors	No. of articles	ISI rating	Country	Affiliation (previous, present)	Publishing year
Zhu, Daoben	98		China	Chinese Academy of Sciences, Nanjing Univ. of Aero./Astronautics	1995–2004
Yoshino, Katsumi	95	Highly cited	Japan	Osaka University	1992–2004
Sariciftci, Niyazi Serdar	93		USA	UC Santa Barbara	1994–2004
Hummelen, Jan-Cornelis	81		USA, Netherlands	UC Santa Barbara, University of Groningen	1995–2004
Iijima, Sumio	80		Japan	NEC Corporation, Meijo University	1996–2004
Ajayan, Pulikel M.	74		France, USA	Universite Paris-Sud, Rensselaer Polytechnic Institute	1995–2004
Kim, M.J.	73		South Korea	Samsung Advanced Inst. of Technology	2000–2004
Ito, Osamu	73		Japan	Tohoku University	1995–2004
Bernier, Patrick	70		France	Universite de Montpellier II	1995–2004
Achiba, Yoji	68		Japan	Tokyo Metropolitan University	1994–2004
Roth, Siegmar	67		Germany	Max-Planck-Inst fuer Festkoerperforschung	1994–2004
Shinohara, Hisanori	63		Japan	Nagoya University	1995–2004
Taylor, Roger	61	Highly cited	UK	University of Sussex	1994–2004
Forro, Laszlo	60		Switzerland	Ecole Polytech.	1994–2004
Prato, Maurizio	57		Italy	Universita di Trieste	1995–2004
Smalley, Richard E.	57	Highly cited	USA	Rice University	1994–2004
Nagy, Janos B.	57		Belgium	Universitaires Notre Dame de la Paix	1995–2004
Yang, Chen	55		USA, Australia	Univ of Kentucky, Australian National University	1998–2004
Iwasa, Yoshihiro	54		Japan	Japan Advanced Inst of Science and Technology, Tohoku University	1995–2004
Kataura, Hiromichi	54		Japan	Tokyo Metropolitan University	1997–2004
Blau, Werner J.	53		Ireland	Trinity College Dublin	1996–2004
Dresselhaus, Millie S.	53		USA	MIT, Univ of Kentucky, MIT	1995–2004
Friend, Richard H.	52	Highly cited	UK	Cambridge University	1992–2004
Guldi, Dirk M.	51		Germany, USA	Hahn-Meitner-Institut Berlin, University of Notre Dame	1997–2004
Nakayama, Yoshikazu	50		Japan	Osaka Prefecture University	1996–2004
Cataldo, Franco	49		Italy	PROGEGA snc, Societa Lupi Chemical Research Inst.	1995–2004
Kikuchi, Kouichi	49		Japan	Tokyo Metropolitan University	1994–2004
Heeger, Alan J.	49	Highly cited	USA	Uniax Corp, UC Santa Barbara	1994–2004
Hirsch, Andreas	48		Germany	Universitat Erlangen-Nurnberg	1994–2004
Meyyappan, Meyya	48		USA	NASA Ames Research Lab	2000–2004

To view a comparative dynamics, we also compared relative advantages of EU, the US, Japan and China (including Hong Kong) who are the most advanced players in nanotech. The nanotech research system of Japan has been gaining strength in the mid-1990s and falling behind in recent years. The decline in the percentage of share in nanotech publications may be because of the new entrants into nanotech basic research activities, such as China. Similar approach was observed in the case of European Union. On the other hand, the US trajectory is moving in the opposite direction to Japan and EU. While China (including Hong Kong) contributes relatively low percentage share than other countries in the Science pole, its distinctive advantage in nanotech is still low (RTA is less than 1), but promising in future.

Nanotechnology research is conducted mainly by universities and public research institutes. The findings scrutinized the top affiliations, top experts involved in nanotech research worldwide, where Asian and American institutions (mostly universities) show their prominent role. The universities can also benefit by their increasing competitiveness in nanotech activities. Private sector accounts only for approximately 7% of scientific articles, with the notable exception of Japan and the United States. Several Japanese and American companies and Korea's Samsung belong to the largest commercial players in the nanotech science pole of the global socio-economic network. The research is particularly useful for technological strategies and science & technology policies, revealing the strengths and weaknesses of the emerging nanotechnological systems. The focus of nanotech research (Science pole) corresponds to the importance of these areas in the commercial domain (Technology and Market poles).

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