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PERSPECTIVES

Global nanotechnology development from 1991 to 2012: patents, scientific publications, and effect of NSF funding

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Abstract In a relatively short interval for an emerging technology, nanotechnology has made a significant economic impact in numerous sectors including semiconductor manufacturing, catalysts, medicine, agriculture, and energy production. A part of the United States (US) government investment in basic research has been realized in the last two decades through the National Science Foundation (NSF), beginning with the nanoparticle research initiative in 1991 and continuing with support from the National Nanotechnology Initiative after fiscal year 2001. This paper has two main goals: (a) present a longitudinal analysis of the global nanotechnology development as reflected in the United States Patent and Trade Office (USPTO) patents and Web of Science (WoS) publications in nanoscale science and engineering (NSE) for the interval 1991–2012; and (b) identify the effect of basic research funded by NSF on both indicators. The interval has been separated into three parts for comparison purposes: 1991–2000, 2001–2010, and 2011–2012. The global trends of patents and scientific publications are presented. Bibliometric analysis, topic analysis, and citation network analysis methods are used to rank countries, institutions, technology subfields, and inventors contributing to nanotechnology development. We then, examined how these entities were affected by NSF funding and how they evolved over the past two decades. Results show that dedicated NSF funding used to support nanotechnology R&D was followed by an increased number of relevant patents and scientific publications, a greater diversity of technology topics, and a significant increase of citations. The NSF played important roles in the inventor community and served as a major contributor to numerous nanotechnology subfields.

Keywords Nanotechnology · Nanoscience · Public funding · Patent analysis · Bibliometric analysis · Citation · Longitudinal evaluation

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Introduction

Nanotechnology is the manipulation and control of matter at the atomic, molecular, and supramolecular scales.[1] It is often viewed as an emerging platform technology that can be used to improve current products and processes (Wang and Shapira 2011).

[1] We use here the National Nanotechnology Initiative definition (http://www.nano.gov).

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This underlying technology has a vast array of applications in various industries including healthcare, the environment, natural resources, construction, food systems, and services. Numerous discoveries made over the past two decades have changed the focus of nanoscale science and engineering (NSE) academic and industrial research and development (R&D) activities. The creation of the US National Nanotechnology Initiative (NNI) in fiscal year 2001 led to increased public funding for nanotechnology (Roco 2000), including for basic research at the National Science Foundation (NSF). The increase in NSE-related funding, from $3M in 1991 for nanoparticles to $150M in 2001 and to more than $460M in 2012, can be correlated with a concomitant increase in academic research output (i.e., scientific publications) and commercial technology development (i.e., patents).

Patents are defined by the US Patent and Trademark Office (USPTO) as a property right granted by the government to an inventor; the rights conferred with property ownership exclude others from making use of the invention for a certain period of time. Patents are an important form of intellectual property and are an essential and rich source of information when examining growth in a particular technology area (Sastry et al. 2010). Most countries maintain patent systems that manage the filing and issuance of patents. The USPTO, for example, now receives over 500,000 patent applications per year[2] and granted about 225,000 utility patents in 2012.[3] NSE-related patents represent the fastest growing technology field in the USPTO patent database after 2001 (Huang et al. 2005).

Scientific paper publications also contribute to technology development in many ways and are a major source of knowledge transfer from public research to industrial application. Research has shown that scientific publications are receiving an increasing number of citations from patents (Beise and Stahl 1999).

Assessing the impact of public funding on science and technology development is essential in decision making and R&D planning. A strong correlation between research funding and papers has been identified (Adams and Griliches 1998). Federal research funding to universities has been correlated with the increase in the number of papers and patents, as well as an increase in faculty salaries (Payne and Siow 2003). Narin (1998) found that approximately 73 % of the papers cited by US industry patents were based on publicly funded research. It has also been demonstrated that public funding can positively lead to the growth of technology-related productivity and employment (Piekkola 2007). More recently, research has empirically shown how public funding fueled industry innovation and economic growth in the biomedical industry (Toole 2012).

However, in the nanotechnology field, there is a need for direct assessment of the longitudinal impact of public funding on both commercial technology development and academic research output. In our previous work, we provided a longitudinal analysis on the impact of NSF funding on nanotechnology patents for 1991–2002 (Huang et al. 2005). Because more than 20 years have passed since the beginning of the first nanotechnology-related program solicitation at NSF in 1991, it is important to update our understanding of how nanotechnology development has evolved over the past two decades and been influenced by public funding. Selected preliminary results on the past two decades have been reported in recent research (Chen et al. 2013). In this study, we extended the work of Huang et al. (2005) on patents for a longer time frame (1991–2012) and examine the longitudinal impact of public funding on both NSE-related USPTO Patents as well as Thomson-Reuters Web of Science (WoS) scientific publications. Scientific assessment of the implications of public funding on overall science and technology development is a complex task (Adams and Griliches 1998). In this study we employed bibliometric analysis, topic analysis, and citation analysis to evaluate the key entities (countries, institutions, inventors, and technology subfields) that are prominent in nanotechnology development. We also explored how public funding of basic research through NSF affected the key entities over three time periods of the past two decades: 1991–2000 (pre-NNI), 2001–2010, and 2011–2012 (NNI).

[2] US Patent and Trademark Office, "Performance and Accountability Report, fiscal year 2012." Accessed 14 February 2013 at http://www.uspto.gov/about/stratplan/ar/USPTOFY2012PAR.pdf.

[3] US Patent and Trademark Office, "All Technologies Report, January 1, 1987 – December 31, 2011," March 2012. Accessed 14 February 2013 at http://www.uspto.gov/web/offices/ac/ido/oeip/taf/all_tech.pdf.

The first part of this paper describes the research framework used for the longitudinal analysis. The second part presents the award, patent, and scientific publication data used in this study and the results from the bibliometric, topic, and citation analyses.

Research framework

Our research framework follows three steps: data acquisition, data preparation, and analysis (Fig. 1).

Data acquisition

We used a keyword search approach to identify the NSE-related award, scientific publication, and patent data from the NSF, WoS, and USPTO databases, respectively. The keywords are based on the NNI definition of nanotechnology and were previously used in nanotechnology patent studies (Huang et al. 2005; Li et al. 2007). For NSF award data and WoS scientific publications, the search was performed on "title" and "abstract" sections. For patents at USPTO we searched the keywords in "title," "abstract," and "claim" sections. Our collection covers data from January 1991 to December 2012.

Data preparation

Name variations and a lack of standardization have been observed in certain data fields, including NSF Principal Investigators (PIs), patent inventors, paper authors, and institutions. For example, "Hewlett-Packard Development Company L.P." may be used in award data while "Hewlett-Packard" is used in patent data. In order to identify which patent inventors or publication authors were funded by NSF grants, we resolved name variations by using a fuzzy string matching algorithm. The algorithm works by building a token-based index for each input string (e.g., name+institution+state+country for a patent inventor). Each string is tokenized and compared to the indices, and its similarity and confidence scores are calculated. The similarity score is the percentage of shared tokens, and the confidence score is negatively related to the number of highly similar matches. If the similarity and confidence scores of a new input string for a match are higher than thresholds, the input string is resolved to the match. In our study, both thresholds were set to 0.9.

Analysis

The 22-year longitudinal evolution of nanotechnology was evaluated by comparing the outcomes in three

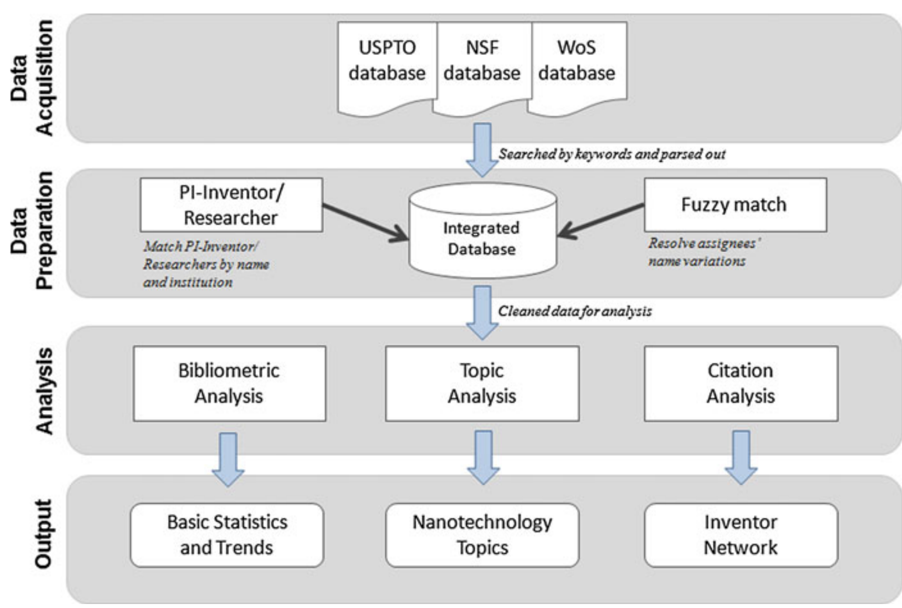

Fig. 1 Research framework

intervals (1991–2000, 2001–2010, and 2011–2012) using three types of analyses:

- *Bibliometric analysis* of award, patent, and scientific publications data identifies development of nanotechnology by countries, institutions, inventors, and technology subfields.
- *Topic analysis* of awards, patents, and scientific publications identifies topic changes over time using document clustering techniques.
- *Citation analysis* utilizes social network analysis to build a network of inventors, assess the relationships among these inventors, and identify the most influential inventors and corresponding patents.

We also evaluated the impact of public funding on basic research by comparing the citation counts of inventors who received NSF funding (i.e., PIs for NSF awards) with others who did not.

Data and observations

Bibliometric analysis

Table 1 presents a summary of the NSE-related award, patents, and scientific publications data sets. The data collected included 19,465 NSF awards, 35,431 patent records from USPTO, and 801,887 scientific publications from Thomson-Reuters' WoS database. The number of NSE-related awards and patents in the 2000s increased by about four times as compared to the 1990s, while the number of scientific publications increased by about five times.

The *first decadal growth rate G1* is defined as the number of awards/patents/papers published during 2001–2010 divided by the respective number of awards/patents/papers during 1991–2000. The *second growth rate G2* is defined by dividing the annual average number of awards/patents/papers in 2011–2012 to the respective annual averages in 2001–2010. The same definitions will be used throughout the paper.

Figure 2 shows the growth of NSE-related patents, scientific publications, and awards from 1991 to 2012. The numbers for the USPTO Patents and WoS publications are for all authors in the respective databases. Patents and scientific publications showed a marked increase in their growth rate beginning in the early 2000s, continuing through 2012. The number of awards stabilized in later years.

Patent data

The USPTO is the federal agency that has a legal mandate to grant patents and register trademarks in the US. Both domestic and foreign inventors may file patent applications with the USPTO and thereby request protection of their intellectual property. There are 103 countries, 21,298 assignees, and 407 first-level US Patent Classification categories included in the 35,431 NSE-related patents in the patent data set. Tables 2, 3, and 4, respectively, identify the patent contributions per country, leading institutions, and top technology fields associated with these patents.

Table 2 shows the top 20 assignee countries in terms of the number of NSE-related patents issued during 1991–2012. During the entire period covered by the study, the US issued the majority of the NSE-related patents to US inventors (23,070; 65 % of all countries), followed by Japan (with 3,332 patents; 9.4 %), South Korea (1,901; 5.4 %), Taiwan (1,170; 3.3 %), and Germany (1,079; 3.0 %).

Examining the decadal growth rate (G1) by country provides a different set of countries, in a different ranked order. The top five countries for growth rate

Table 1 Summary data statistics for NSE-related NSF award, USPTO Patent, and WoS paper collection for PIs and all authors from 1991 to 2012

Data source	Interval					
	1990s (1991–2000)	2000s (2001–2010)	Two years (2011–2012)	All years (1991–2012)	Decadal growth rate G1	Second growth rate G2
NSF awards	3,541	13,149	2,775	19,465	3.71	1.04
USPTO patents	4,839	20,843	9,749	35,431	4.31	2.34
WoS publications	101,481	506,536	193,870	801,887	4.99	1.91

The numbers for the USPTO patents and WoS publications are for all authors, while NSF awards are only for PIs

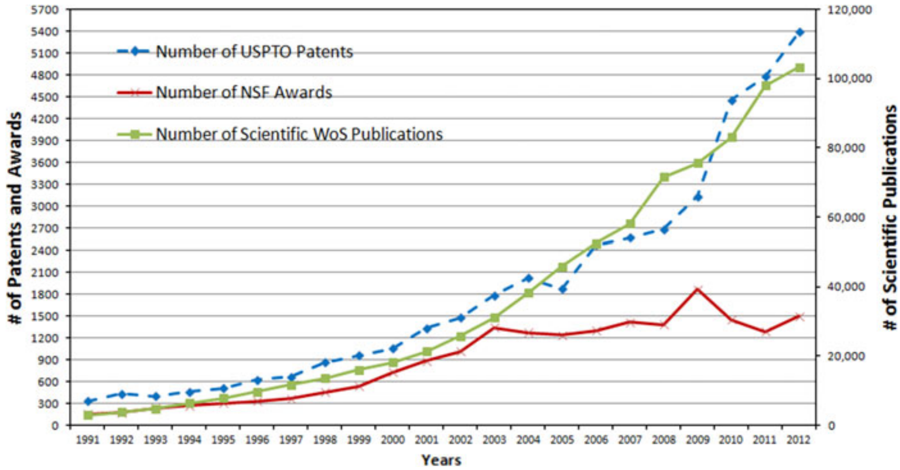

Fig. 2 Trend of NSE-related USPTO patents, WoS scientific publications, and NSF awards

Table 2 Top 20 assignee countries for NSE-related USPTO patents

Rank	Assignee country	Number of patents				Growth rate	
		All years	1991–2000	2001–2010	2011–2012	G1	G2
1	United States	23,070	3,597	13,947	5,526	3.88	1.98
2	Japan	3,332	534	1,983	815	3.71	2.05
3	Korea (South)	1,901	32	1,114	755	34.81	3.39
4	Taiwan	1,170	62	521	587	8.40	5.63
5	Germany	1,079	119	687	273	5.77	1.99
6	France	799	160	396	243	2.48	3.07
7	China	591	1	262	328	262.0	6.26
8	Canada	408	56	256	96	4.57	1.88
9	Netherlands	349	30	198	121	6.60	3.06
10	Switzerland	284	61	156	67	2.56	2.15
11	Australia	218	28	144	46	5.14	1.32
12	UK	216	29	142	45	4.90	1.58
13	Israel	211	17	150	44	8.82	1.47
14	Sweden	165	21	100	44	4.76	2.20
15	Italy	161	24	109	28	4.54	1.28
16	Belgium	144	15	93	36	6.20	1.94
17	Singapore	126	2	90	34	45.00	1.89
18	Finland	72	8	43	21	5.38	2.44
19	India	60	2	28	30	14.00	5.35
20	Denmark	46	15	28	3	1.87	0.54

were China, Singapore, Korea (South), India, and Israel. Of these, only South Korea was also in the top five in terms of the number of patents issued. Examining the second growth rate (G2) for 2011–2012, the leading economies are China, Taiwan, India, Korea (South), and Netherlands.

Of course, within the top 20 countries, there is still a significant difference in the number of patents issued by the top country (US: 23,070 patents 1991–2012) and all other countries (3,332 or fewer). Some portion of this difference can be ascribed to the "home advantage": the tendency of patent filers to file more

Table 3 Top 20 assignees for NSE-related patents

Rank	Assignee name	Number of patents				Growth rate	
		All years	1991–2000	2001–2010	2011–2012	G1	G2
1	International Business Machines Corporation	1,119	190	622	307	3.27	2.47
2	Micron Technology, Inc,	762	43	555	164	12.91	1.48
3	Samsung Electronics Co., Ltd.	681	13	380	288	29.23	3.79
4	The Regents of the University of California	589	120	349	120	2.91	1.72
5	Hewlett-Packard Development Company, L.P.	557	24	429	104	17.88	1.21
6	Xerox Corporation	538	138	259	141	1.88	2.72
7	Hon Hai Precision Industry Co., Ltd.	508	0	250	258	N/A	5.16
8	Intel Corporation	501	17	395	89	23.24	1.13
9	General Electric Company	433	49	297	87	6.06	1.46
10	3M Innovative Properties Company	376	21	261	94	12.43	1.80
11	Massachusetts Institute of Technology	313	42	195	76	4.64	1.95
12	Industrial Technology Research Institute	311	15	228	68	15.20	1.49
13	Eastman Kodak Company	293	81	190	22	2.35	0.58
14	E.I. du Pont de Nemours and Company	267	39	148	80	3.79	2.70
15	Advanced Micro Devices, Inc	247	34	204	9	6.00	0.22
16	Kabushiki Kaisha Toshiba	211	37	123	51	3.32	2.07
17	Motorola Inc	194	91	103	0	1.13	0.00
18	L'Oreal, SA	188	65	118	5	1.82	0.21
19	PPG Industries Ohio, Inc.	178	56	99	23	1.77	1.16
20	NEC Electronics Corporation	175	75	84	16	1.12	0.95

patents domestically than in foreign patent offices (Criscuolo 2006; Dang et al. 2009). The second-ranked country, Japan, had 3,332 patents, about 14 % of the number of US patents. India, one of the lowest ranked countries, had only 60 patents. Even with a decadal growth rate of 14.00, it will still take India quite some time to move up in the ranks.

Table 3 lists the top 20 assignees for NSE-related patents issued during 1990–2012. The top five assignee institutions were International Business Machine Corporation (IBM); Micron Technology, Inc.; Samsung Electronics Co., Ltd.; the Regents of the University of California; and Hewlett-Packard Development Company, L.P. All but one are US institutions. As with the top five countries, when ordered by the growth rate, Hon Hai Precision Industry Co., Ltd; Samsung Electronics Co., Ltd.; Intel Corporation; Hewlett-Packard Development Company, L.P.; and Industrial Technology Research Institute (Taiwan) emerged, in order, as the top five assignee institutions that experienced the most dramatic increase in the number of patents issued during 1991–2010. Considering the more recent growth rate G2, the leading institutions are Hon Hai Precision Industry Co., Ltd.; Samsung Electronics Co.; Xerox; DuPont; and IBM.

Table 4 lists the top 20 technology fields represented by the first level of the US Patent Classification Code. The major technology fields of the NSE-related patents are "Active solid-state devices," "Semiconductor device manufacturing," "Stock material or miscellaneous articles," and "Nanotechnology." Comparing the major NSF Division awards and patent technology fields, we see that the dominant NSF Divisions covering Material research, Design, and Manufacturing innovation were consistent, in part, with the importance of the related technology fields as reflected in the patent data. By computing the growth rate (G1) for each of the top 20 technology fields, we also identified that "Active solid-state-devices," "Semiconductor device manufacturing," and "Nanotechnology" were three of the several fields that grew the most rapidly during the past two decades. Among them, "Class 977: Nanotechnology" was created by

Table 4 Top 20 technology fields by USPTO first-level classification code

Rank	Technology fields	Number of patents				Growth rate	
		All years	1991–2000	2001–2010	2011–2012	G1	G2
1	Active solid-state devices (e.g., transistors, solid-state diodes)	4,649	425	3,269	955	7.69	1.46
2	Semiconductor device manufacturing: process	3,618	371	2,558	689	6.89	1.35
3	Stock material or miscellaneous articles	2,749	545	1,713	491	3.14	1.43
4	Nanotechnology	2,101	0	1,353	748	N/A	2.76
5	Coating processes	1,933	409	1,131	393	2.77	1.74
6	Drug, bio-affecting and body treating compositions	1,680	509	851	320	1.67	1.88
7	Radiant energy	1,643	588	875	180	1.49	1.03
8	Chemistry: molecular biology and microbiology	1,471	297	912	262	3.07	1.44
9	Optics: systems (including communication) and elements	1,103	283	689	131	2.43	0.95
10	Radiation imagery chemistry: process, composition, or product	1,097	301	676	120	2.25	0.89
11	Synthetic resins or natural rubbers—part of the class 520 series	1,069	197	687	185	3.49	1.35
12	Drug, bio-affecting and body treating compositions	1,022	366	487	169	1.33	1.74
13	Compositions	1,015	166	622	227	3.75	1.82
14	Optics: measuring and testing	888	218	551	119	2.53	1.08
15	Chemistry: analytical and immunological testing	853	218	491	144	2.25	1.47
16	Chemical apparatus and process disinfecting, deodorizing, preserving, or sterilizing	818	156	491	171	3.15	1.74
17	Optical waveguides	632	103	462	67	4.49	0.73
18	Organic compounds—part of the class 532–570 series	440	80	291	69	3.64	1.19
19	Chemistry: natural resins or derivatives; peptides or proteins; lignins or reaction products thereof	436	112	243	81	2.17	1.67
20	Organic compounds—part of the class 532–570 series	143	58	69	16	1.19	1.16

USPTO as a cross-reference-art collection class in 2004. This class grew quickly and was ranked in the top 20 with 2,101 patents through 2012.

WoS scientific publication data

For NSE-related scientific publication data, we conducted country analysis and institution analysis to identify the top countries and institutions that published the most scientific literature. Table 5 lists the top 20 countries in terms of the number of scientific publications produced during 1991–2012, with the top five countries in ranked order being the USA., China (PRC), Japan, Germany, and France.

In the 1990s, China (PRC) was ranked 5th in publishing NSE-related scientific literature, but by the 2000s China had moved to second place, publishing 94,685 publications. In 2010, China surpassed the US in the number of scientific publications produced and has held onto that status through 2012, the most current data available. For other economies with high decadal growth rates (G2), Taiwan experienced the most significant growth in NSE-related publications, followed by China (PRC), South Korea, Singapore, and India. Based on the growth rate (G2) for 2011–2012, two EU countries entered the top five: India, Singapore, Italy, Spain, and Australia.

Table 6 lists the top 20 research institutions that published the highest number of nanotechnology papers during 1991–2012. The Chinese Academy of Sciences published the most (China), followed by the Russian Academy of Sciences (Russia), the Centre National De La Recherche Scientifique (CNRS; France), and the University of Tokyo and Osaka

Table 5 Top 20 countries by the number of WoS scientific publications

Rank	Country	Number of WoS scientific publications				Growth rate	
		All years	1991–2000	2001–2010	2011–2012	G1	G2
1	USA	204,273	34,081	129,624	40,568	3.80	1.56
2	China (PRC)	146,420	6,062	94,685	45,673	15.62	2.41
3	Japan	75,850	14,246	48,976	12,628	3.44	1.29
4	Germany	50,891	9,390	32,751	8,750	3.49	1.34
5	France	44,503	6,092	28,859	9,552	4.74	1.65
6	South Korea	41,907	1,783	27,585	12,539	15.47	2.27
7	England	34,246	4,632	22,170	7,444	4.79	1.68
8	India	22,285	1,116	12,014	9,155	10.77	3.81
9	Italy	21,474	2,682	12,221	6,571	4.56	2.69
10	Russia	21,182	2,965	13,244	4,973	4.47	1.88
11	Spain	21,054	1,889	12,686	6,479	6.72	2.55
12	Canada	20,960	2,185	13,017	5,758	5.96	2.21
13	Taiwan	18,449	712	14,221	3,516	19.97	1.24
14	Australia	14,728	1,068	9,117	4,543	8.54	2.49
15	Switzerland	13,664	2,046	8,517	3,101	4.16	1.82
16	Netherlands	12,266	1,567	7,983	2,716	5.09	1.70
17	Singapore	10,147	478	5,905	3,764	12.35	3.9
18	Poland	7,953	893	5,473	1,587	6.13	1.45
19	Brazil	7,097	720	5,017	1,360	6.97	1.36
20	Sweden	6,624	1,255	4,314	1,055	3.44	1.22

University (both of Japan). Interestingly, when the institutions are ranked by country for number of scientific publications, China itself came in second, followed by Japan in third (which produced only about half of the number of papers of China), France in fifth, and Russia in tenth. In terms of decadal growth rate G1, the top five research institutions were Zhejiang University (China), Indian Institutes of Technology (India), Seoul National University (South Korea), Chinese Academy of Sciences (China), and the National University of Singapore.

NSF award data

The National Science Foundation plays a significant role in supporting US research in many science and engineering areas, including NSE. NSF awards account for approximately 20 % of federal support of basic research (in all fields) provided to academic institutions.[4] The NSF is organized broadly into several directorates, and each directorate in turn oversees several divisions. Awards are generally issued by programs, which may be organized under one or more Divisions and/or under an NSF-wide office.

The data set for the NSE-related awards included 19,465 awards from 59 divisions and 863 programs from 1991 to 2012. The total number of NSF awards related to NSE (topics/areas) was 3,541 in 1991–2000; 13,149 in 2001–2010; and 2,775 in 2011–2012, with a decadal growth rate (G1) of 371 % for the second interval.

Topic analysis

The patents, scientific publication, and NSF award data collected for this study covered the range of NSE-related topics. To analyze the nanotechnology topics covered by the data, we employed a series of computational linguistics techniques to cluster the documents into topics.

For award data, terms were extracted from the title and abstract; for patents and publication data, terms

[4] National Science Foundation, "About Awards." Accessed 21 February 2013 at http://www.nsf.gov/awards/about.jsp.

Table 6 Top 20 institutions by the number of WoS scientific publications

Rank	Research institution	Number of WoS scientific publications				Growth rate	
		All years	1991–2000	2001–2010	2011–2012	G1	G2
1	Chinese Acad Sci	29,591	1,506	19,760	8,325	13.12	2.11
2	Russian Acad Sci	12,543	1,421	8,477	2,645	5.97	1.56
3	CNRS	8,105	956	5,458	1,691	5.71	1.55
4	Univ Tokyo	6,932	1,067	4,656	1,209	4.36	1.30
7	Osaka Univ	6,613	906	4,088	1,619	4.51	1.98
5	Tohoku Univ	6,266	897	4,225	1,144	4.71	1.35
8	Univ Calif Berkeley	5,936	844	3,696	1,396	4.38	1.89
12	CSIC	5,585	497	3,816	1,272	7.68	1.67
10	Univ Illinois	5,580	819	3,658	1,103	4.47	1.51
9	MIT	5,567	731	3,594	1,242	4.92	1.73
6	Nat'l Univ Singapore	5,535	323	4,162	1,050	12.89	1.26
13	Univ Sci & Technol China	5,527	442	3,620	1,465	8.19	2.02
17	Peking Univ	5,294	353	3,173	1,768	8.99	2.79
16	Indian Inst Technol	5,123	193	3,531	1,399	18.3	1.98
19	Univ Cambridge	5,040	515	3,192	1,333	6.2	2.09
11	Nanjing Univ	5,035	409	3,614	1,012	8.84	1.40
14	Zhejiang Univ	4,836	88	3,453	1,295	39.24	1.88
15	Seoul Natl Univ	4,831	261	3,635	935	13.93	1.29
18	CNR	4,679	483	3,246	950	6.72	1.46
20	Kyoto Univ	4,540	535	3,063	942	5.73	1.54

were extracted from their title-abstract-claims and title-abstract-keywords as defined earlier. This first step resulted in each document (whether award, patents, or paper) being represented by a feature vector consisting of the terms used in the textual part of the document and a count of each term. As is typical in text processing, the number of terms was extremely high and many were irrelevant to topic identification. An entropy-based feature selection method was then used to remove the noisy terms and improve the feature space representation (Liu et al. 2003). After constructing feature vectors for the documents, expectation–maximization (EM) clustering was used to group documents that had a high similarity in term usage. EM clustering was chosen because it automatically determined the optimal number of topic clusters. It is also robust against noise, highly skewed data, and high dimensionality, which are commonly observed in text mining problems (Ordonez and Cereghini 2000; Surdeanu et al. 2005; Fazayeli et al. 2008). From the resulting document clusters, the top key phrases can be used to infer the topic of the documents belonging to the cluster.

Document clustering was implemented separately on the NSE-related patents, scientific publication, and NSF award datasets to identify the technology topics associated with each. As can be seen in the resulting analysis, nanotechnology topics changed significantly during a relatively short period of time.

Patent topics

Tables 7 and 8 show all the topics identified in NSE-related patent data during 1991–2000 and 2001–2010, respectively, ordered by the number of patents associated with each topic. From 1991 to 2000, NSE-related patents covered broader technology topics (35 major topics) than the award data. As shown in Table 7, the top five topics include "nucleic acid," "carbon atom," "thin film," "semiconductor device," and "laser beam." From 2001 to 2010, 47 topics were identified; "semiconductor device," "nucleic acid," "light source," "optical fiber," and "electron beam" were the topics that had the highest number of associated patents. During this period, six of the top

Table 7 Topics identified from USPTO patent data (1991–2000)

Rank	Topic	Number of patents	Rank	Topic	Number of patents
1	Nucleic acid	842	19	Polymeric material	34
2	Carbon atom	593	20	X-ray	32
3	Thin film	529	21	Metal ion	29
4	Semiconductor device	508	22	Memory cell	23
5	Laser beam	421	23	Host cell	18
6	Aqueous solution	415	24	Metal oxide	14
7	Optical fiber	334	25	Imaging system	12
8	Pharmaceutical composition	314	26	Ink composition	12
9	Light source	238	27	Photographic element	10
10	Delivery system	199	28	DNA sequence	9
11	Magnetic field	192	29	Enzymatic RNA molecule	9
12	Integrated circuit	191	30	Laser light	9
13	Probe microscopy	138	31	Abrasive article	9
14	Toner composition	73	32	Particle size	9
15	Glass composition	59	33	Supporting substrate	8
16	Carbon black	44	34	Grams benzene	8
17	Physical property	42	35	Active layer	7
18	Molecular weight	35			

ten patent topics overlapped with the top ten patent topics from 1991 to 2000: “semiconductor device,” “nucleic acid,” “light source,” “optical fiber,” “thin film,” and “pharmaceutical composition.”

Several health-related NSE topics, such as “pharmaceutical composition,” “therapeutic agent,” and “pharmaceutically acceptable salt,” were identified from patent, but not award, data. This finding may suggest that developments in health-related NSE areas were led primarily by private companies.

Figure 3 shows the comparison between patent topics for 1991–2000 and 2001–2010. The radial dimension is in direct proportion with the log-scaled number of patents for the respective topic. The closer a topic data point is to the rim, the higher the number of patents associated with the topic. All topics are placed in a clockwise direction, ordered by their growth rate from the 1990s (red line) to the 2000s (blue line). The green dashed-line ellipse (right side) marks the 31 emerging topics in 2000s from a total of 47 topics. Ordered by growth rate, the top five emerging topics were “electron beam,” “fluid communication,” “functional group,” “amino acid,” and “composite material.” The red dotted-line ellipse (left side) marks the topics that did not carry over to the 2000s.

Scientific publication topics

Tables 9 and 10 list all topics identified in the WoS scientific publication data for 1991–2000 and 2001–2010, respectively, ordered by the number of publications within each topic. Twenty-six topics were discovered for 1991–2000. The top five topics for this period included “atomic force (microscopy),” “quantum dot,” “molecular modeling,” “carbon nanotube,” and “grain size.” Thirty-one topics were identified for 2001–2010. “Carbon nanotube,” “atomic force,” “quantum dot,” “mechanical properties,” and “molecular modeling” were the top five topics with the highest number of associated scientific publications.

Figure 4 shows the comparison between publication topics in 1991–2000 and 2001–2010. All topics are placed in a clockwise direction by their growth rate from the 1990s to the 2000s. The green circle (right side) marks 16 emerging topics in the 2000s (out of 31). Ordered by the growth rate, the top five emerging topics were “photocatalytic activity,” “solar cell,” “catalytic activity,” “molecular dynamics simulation,” and “drug delivery.” The red dotted-line ellipse (left side) marks the dead topics that were not identified in the 2000s.

Table 8 Topics identified from USPTO Patent data (2001–2010)

Rank	Topic	Number of patents	Rank	Topic	Number of patents
1	Semiconductor device	2,829	25	Fatty acid	194
2	Nucleic acid	1,915	26	Rare earth	178
3	Light source	1,843	27	Dielectric layer	172
4	Optical fiber	1,146	28	Host cell	125
5	Electron beam	1,023	29	X-ray	101
6	Fluid communication	895	30	Semiconductor structure	96
7	Thin film	747	31	Information storage medium	61
8	Pharmaceutical composition	746	32	Nucleic acid molecule	57
9	Integrated circuit	735	33	Material layer	43
10	Functional group	732	34	Particle size	41
11	Carbon atom	709	35	Alkyl group	28
12	Aqueous solution	702	36	Ion source	26
13	Amino acid	659	37	Magnetic component	22
14	Composite material	553	38	Charge transport layer	20
15	Fuel cell	553	39	Semiconductor wafer	18
16	Memory cell	495	40	Semiconductor material	17
17	Mass spectroscopy	463	41	Heterocyclic compound	16
18	Therapeutic agent	456	42	Photoacid generator	15
19	Control system	453	43	Light emitting device	14
20	Pharmaceutically acceptable salt	449	44	Carbon nanotube	12
21	Probe microscopy	420	45	Light emitting layer	11
22	Communication system	416	46	Organic compound	10
23	Magnetic field	388	47	Metal ion	8
24	Magnetic recording medium	379			

NSF a award topics

Tables 11 and 12 show all topics identified in the NSE-related award data during 1991–2000 and 2001–2010, respectively, ordered by the number of awards associated with each topic. During 1991–2000, 26 topics were identified. In this period, the NSE-related NSF awards were concentrated in several technology areas including "thin film," "molecular modeling & simulation," "atomic force microscopy," and "scanning tunneling microscopy." Thin film had the highest number of awards (576) with an average funding amount of $361,092. During 2001–2010, the topics most funded by NSF were "thin film," "carbon nanotube," "mechanical property," "single molecule," and "magnetic field," from 46 topics identified in total.

Of the top 10 technical topics for 1991–2000 and for 2001–2010, only four topics overlapped: thin film, molecular simulation, atomic force microscopy, and mechanical property. This suggests that the major areas of NSE-related awards changed faster over time than NSE-related patents (six topics out of the top ten overlapped) and scientific literature (seven topics out of the top ten overlapped).

Figure 5 uses a radar chart to visualize a comparison between award topics for 1991–2000 and 2001–2010, respectively. Topics are placed in a clockwise direction, ordered by their growth rate from the 1990s to the 2000s. The green dashed-line ellipse (right side) marks the area where new topics emerged during the 2000s. Ordered by the growth rate, the top five emerging topics in the 2000s included "thin film," "carbon nanotube," "single molecule," "molecular dynamics," and "quantum dot." The red dotted-line ellipse (left side) marks the area of topics that died out in the 1990s.

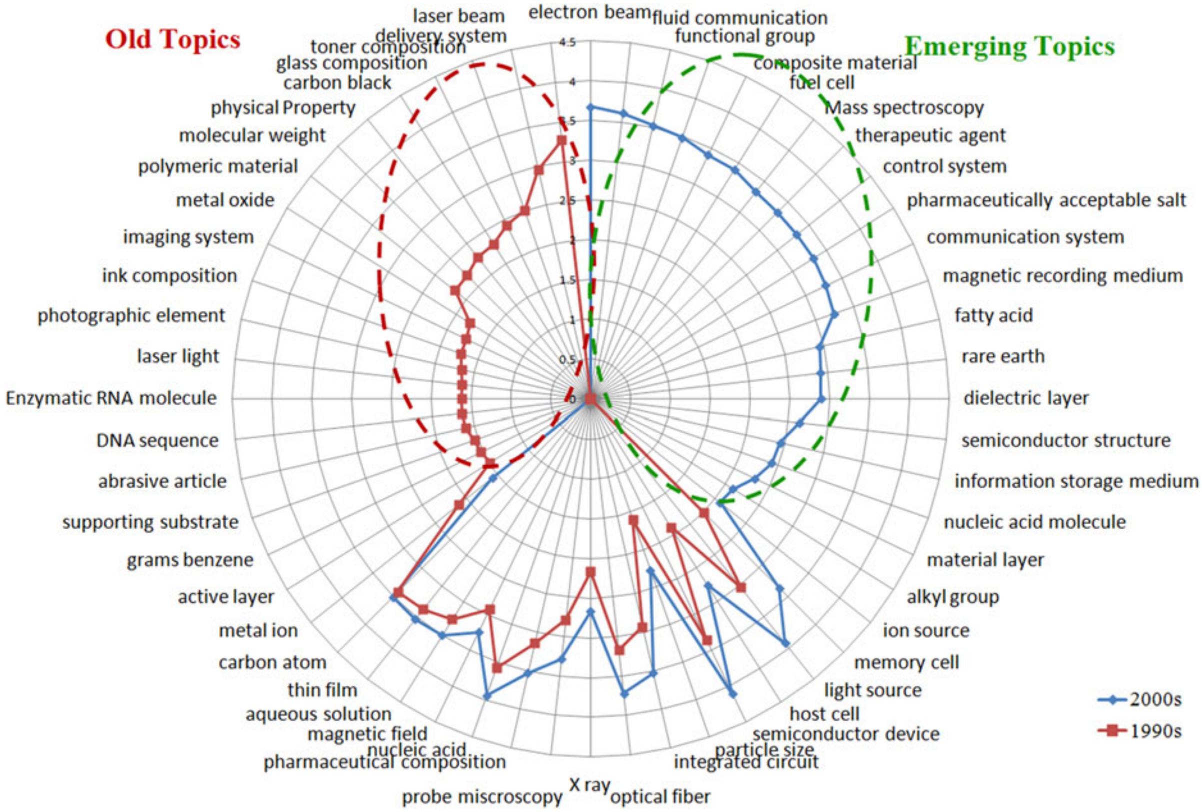

Fig. 3 Comparison of the NSE-related patent topics between the 1990s and the 2000s

Table 9 Topics identified from WoS scientific publication data (1991–2000)

Rank	Topic[a]	Number of publications	Rank	Topic	Number of publications
1	Atomic force (microscopy)*	9,002	14	Binding site	185
2	Quantum dot	4,657	15	Molecular simulation*	177
3	Molecular modeling*	3,297	16	Detection limit	172
4	Carbon nanotube	1,486	17	Cell line	145
5	Grain size	1,128	18	Mass spectrometry	143
6	Quantum effect*	934	19	*Molecular weight*	140
7	Room temperature	625	20	Heterotrophic nanoflagellates	130
8	STM image	574	21	Alkyl chain	122
9	Magnetic property	467	22	GOLD ELECTRODE	122
10	*Particle size**	323	23	*Thin film**	113
11	Optical property	288	24	Spatial resolution	107
12	Mechanical properties*	276	25	Crystal structure	94
13	Gold surface	249	26	Molecular dynamic	81

[a] Topics marked with an asterisk (*) overlapped with topics identified in the Award data in the same period. Topics italicized overlapped with topics identified in the patent data in the same period

Table 10 Topics identified from WoS scientific publication data (2001–2010)

Rank	Topic[a]	Number of publications	Rank	Topic	Number of publications
1	*Carbon nanotube**	37,435	17	Room temperature	1,336
2	Atomic force (microscopy)*	22,728	18	Grain size	1,154
3	Quantum dot*	17,402	19	Optical property	1,107
4	Mechanical properties*	6,270	20	Gold surface	1,016
5	Molecular modeling*	4,241	21	Crystal structure	908
6	Photocatalytic activity	3,236	22	*Aqueous solution*	901
7	*Particle size**	2,785	23	Density functional theory	802
8	Solar cell	2,676	24	Temperature dependence	716
9	Magnetic property	2,612	25	Surface plasmon	481
10	*Thin film*	2,386	26	Flow rate	466
11	Detection limit	2,379	27	Grain boundary	433
12	Catalytic activity	2,078	28	Polymer chain	276
13	Molecular_dynamics simulation	1,851	29	Photonic crystal	220
14	Drug delivery*	1,668	30	Quantum effect*	214
15	Molecular weight	1,662	31	NF membrane	205
16	Stem cell	1,357			

[a] Topics marked with an asterisk (*) overlapped with topics identified in the Award data in the same period. Topics italicized overlapped with topics identified in the patent data in the same period

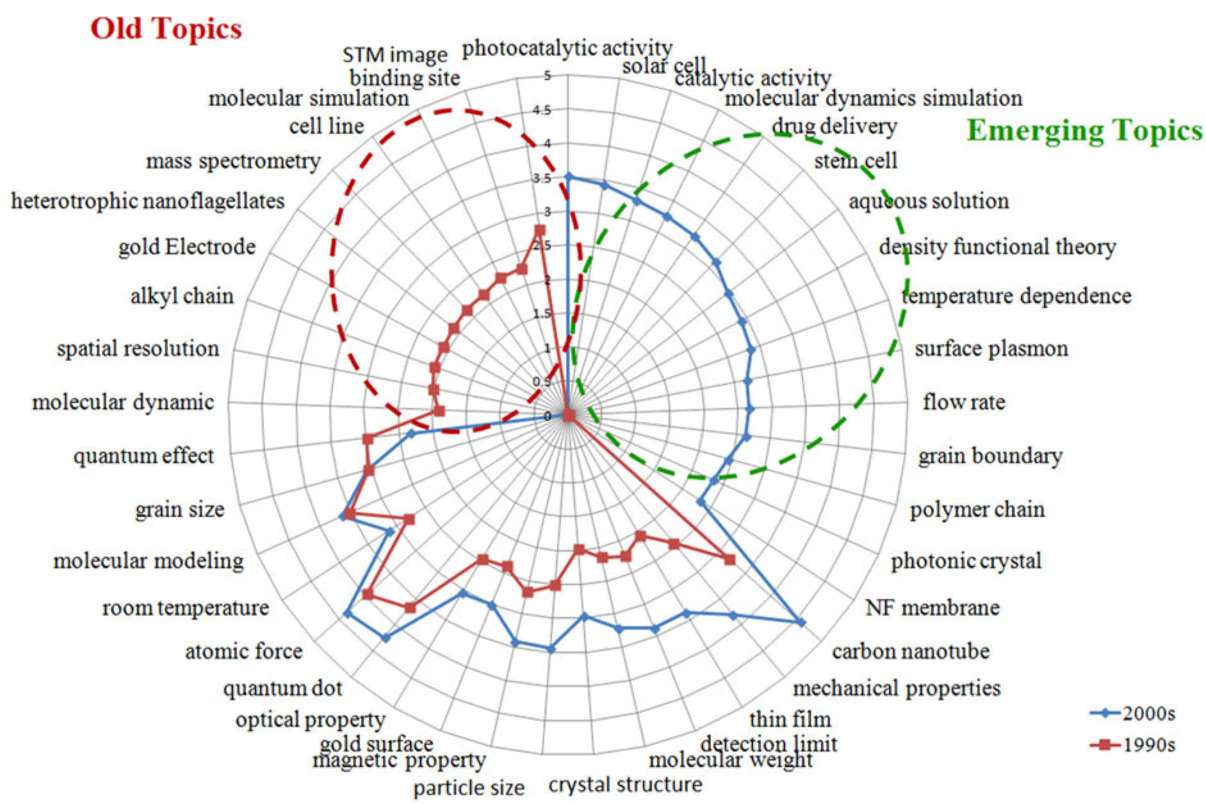

Fig. 4 Comparison of the NSE-related scientific publication topics from two decades

Table 11 Topics identified from NSF award data (1991–2000)

Rank	Topic	Number of awards	Average award amount ($)	Rank	Topic	Number of awards	Average award amount ($)
1	Thin film	576	361,092	14	Transmission electron microscopy	50	307,072
2	Molecular modeling	551	279,955	15	Water column	50	247,774
3	Molecular simulation	513	336,016	16	Molecular motor	41	268,293
4	Atomic force microscopy	422	362,467	17	Magnetic field	40	476,009
5	Scanning tunneling microscopy	331	346,853	18	Semiconductor quantum	33	239,414
6	Electronic device	141	446,214	19	Nanostructured Material	33	537,215
7	Advanced material	134	884,116	20	Nanocomposite Material	32	556,445
8	Transition metal	114	404,883	21	Electron microscopy	19	201,483
9	X-ray	110	622,758	22	Thermodynamic Property	19	188,684
10	Mechanical property	98	242,950	23	Chemical vapor deposition	17	913,608
11	Self-assembled monolayers	58	296,475	24	Nuclear magnetic resonance	16	231,862
12	Quantum effect	57	316,594	25	Molecular electronics	13	175,854
13	Solid state	57	237,814	26	Particle size	10	306,095

Citation analysis

In citation analysis, an inventor network is constructed according to the patent citation relationships. In a citation network, the link from inventor A to inventor B is established if A's patent cites B's patent. Of particular interest in this study are the positions of the "PI-inventors"—the NSE-related patent inventors who are also funded principal investigators (PIs) in NSF awards.

To evaluate the contribution and influence of PI-inventors in the network, we conducted critical patent/inventor analysis and PageRank analysis.

Critical patent/inventor analysis

The aim of critical inventor/patent analysis is to measure the individual performance of PI-inventors and their patents. Specifically, the critical PI-inventors and patents that excelled in the top 20 NSE subfields were identified based upon the number of citations they received. The number of citations, or citation count, is often used to measure the impact of articles, journals, and researchers (Kulkarni and Aziz 2009). High citation counts of a patent indicate that it may have a high technological or economical value (Igami and Okazaki 2007). Similarly, a citation implies an acknowledgement of authority from the citing author to the cited one, and the total number of citations an author receives may relate to the community's recognition of him/her (King 1987). Therefore, frequently cited patents are of great value, and an inventor with a high number of citation counts can be considered to be making a significant contribution to the field.

Tables 13 and 14 list the top 20 nanotechnology subfields (identified by the first-level US Patent Classification Code), ordered by the number of NSE-related patents in each, and the PI-inventors' patents that received the highest number of citations in that subfield. For example, in Table 13, the subfield "257: Active solid-state devices (e.g., transistors, solid-state diodes)" encompassed 3,694 NSE-related patents. Within this subfield, the most highly cited patent owned by a PI-inventor was Patent no. 6487106, titled "Programmable microelectronic devices and method of forming and programming same," with 101 citations; among all patents in the subfield, it was the fifth most-highly cited. Table 13 shows that in 14 out of 20 subfields, the most frequently cited PI-inventors' patents ranked within the top 20 of all patents in the corresponding subfield.

Table 14 lists the most-highly cited PI-inventors for each of the top 20 subfields. Similarly to Table 13, it shows that in 14 of the 20 subfields, the PI-inventors ranked within the top 20 among all inventors in the

Table 12 Topics identified from NSF award data (2001–2010)

Rank	Topic	Number of grants	Average award amount ($)	Rank	Topic	Number of grants	Average award amount ($)
1	Thin film	2,734	412,303	17	X-ray	160	935,747
2	Carbon nanotube	1,142	338,398	18	Drug delivery	139	355,292
3	Mechanical property	860	345,451	19	Quantum computing	133	249,503
4	Single molecule	730	558,914	20	Transition metal	124	269,223
5	Magnetic field	545	366,727	21	Molecular electronics	65	380,643
6	Molecular dynamics	473	373,473	22	Complex fluids	64	229,404
7	Molecular Simulation	416	315,389	23	Technology Transfer	64	308,727
8	Nuclear Magnetic Resonance	385	328,731	24	Magnetic Material	63	629,652
9	Quantum dot	384	423,377	25	Composite material	60	696,583
10	Atomic Force Microscopy	371	318,145	26	Quantum information	60	559,291
11	Molecular motor	294	397,537	27	Raman scattering	46	316,937
12	Solid State	263	293,660	28	Transport Systems	41	297,654
13	Molecular modeling	245	504,159	29	Electronic Transport	38	275,279
14	Integrated circuit	235	334,343	30	Nanoscale devices	36	248,289
15	Environmental monitoring	198	437,679	31	Electronic property	35	420,560
16	Magnetic nanoparticles	196	387,284	32	Thermal Transport	35	390,305
33	Fuel cell	32	271,226	34	Polymer material	28	277,571
35	Solid particle	26	162,864	41	Condensed matter	16	154,160
36	Synthetic polymers	26	271,810	42	Electronic system	14	246,188
37	Tissue engineering	25	216,968	43	Computational method	13	348,790
38	Information processing	25	1,220,592	44	Transport property	13	357,941
39	Computational technique	19	202,503	45	Heat transfer	12	233,751
40	Biological systems	17	206,403	46	Organic Material	10	191,711

corresponding subfield. Considering that the number of all patents in each technology subfield ranged from approximately 127 to 3,694, the results indicate that PI-inventors and their patents contributed significantly, through various subfields, to nanotechnology development. Conversely, the data also indicate areas in which NSF funding has had less impact, such as 514: Drug, bio-affecting and body-treating compositions, where the most highly cited PI-inventor is ranked 177th. This may reflect the dominant role of NIH funding in that subfield, while NSF PIs covered fewer medical research topics.

PageRank analysis

Evaluating the influence of patent inventors solely through the metrics of their patents or citations reveals only a portion of their influence. Using PageRank analysis to discern the relationships between inventors allows the global roles that PI-inventors play in the entire inventor network to be further explored and assessed.

PageRank measures the influence of each inventor in a network by using a link analysis algorithm (Brin and Page 1998). Similar to the basic citation count, the PageRank algorithm views a citation to an inventor as a "vote" for that inventor's importance. In addition, the algorithm weighs those "votes" according to the importance of the voters. An inventor would be considered more important if he/she receives more votes from other important inventors (voters). Therefore, an inventor with a high PageRank score is likely to be playing an important role in the entire network and have greater influence on the community.

Figure 6 shows the citation network of inventors and the results of running the PageRank algorithm on it. PI-inventors are represented by red nodes, while non-PI-inventors are black nodes. The size of each inventor node is proportional to its PageRank score. For better visualization, only inventors with more than

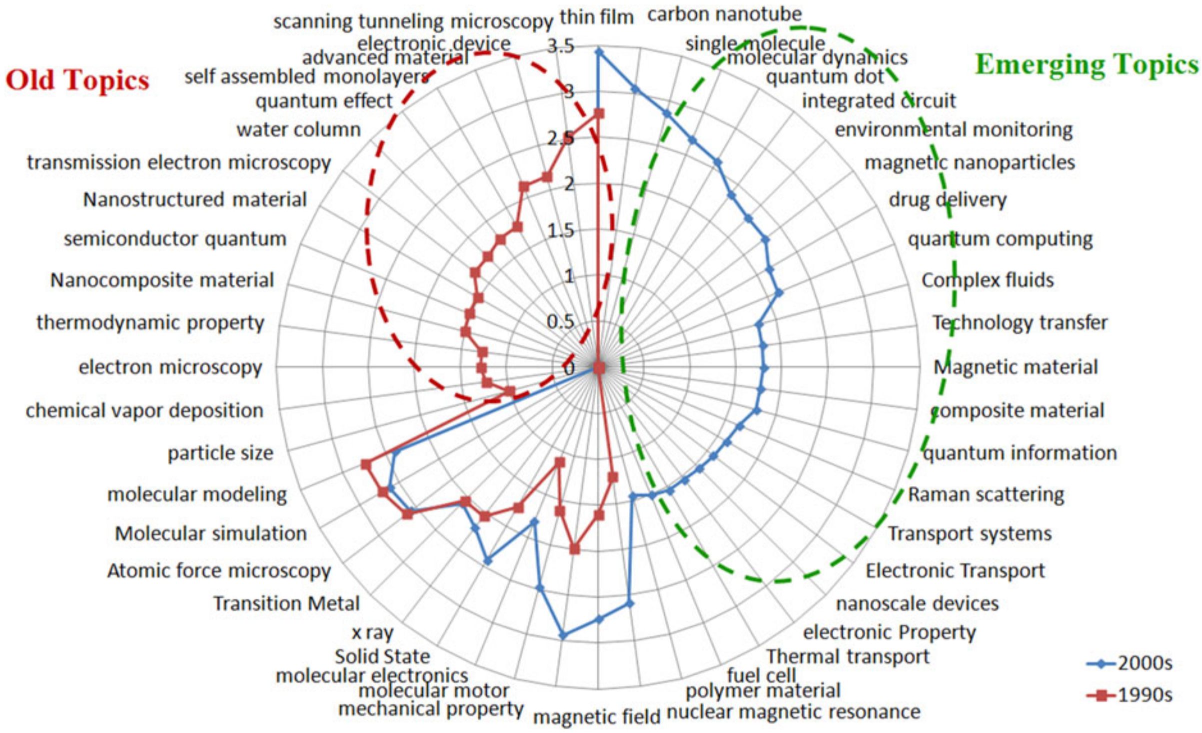

Fig. 5 Comparison of the NSE-related award topics from two decades

25 citations were plotted. Among the top 30 inventors in terms of the PageRank score, 4 (13.3 %) were PI-inventors: Lieber, Charles M. from Harvard University (ranked 6th); Whitesides, George M. from Harvard University (21st); Lindsey, Jonathan S. from North Carolina State University (23rd); and Lindsay, Stuart M. from Arizona State University (28th) (the last inventor is not shown in the network because his citation number is below 25). Considering that only 1.3 % (1,887) among all 140,855 NSE-related patent inventors were PI-inventors, this result suggests significant roles for PI-inventors in the entire network.

Citations received by NSF PI-inventors

Results in the previous section showed that individual PI-inventors played important roles in the nanotechnology inventor citation network. We further evaluated the impact of PI-inventors as a group, by comparing the number of citations they received with other representative groups. These comparison groups were also used in our previous study (Huang et al. 2005):

(1) IBM inventors, the biggest assignee institution (see Table 3).
(2) Inventors from the top ten research institutions (see Table 6).
(3) Inventors from the University of California (UC), the biggest academic assignee institution (see Table 3).
(4) Inventors from the United States (US).
(5) Inventors identified in the entire data set (Entire Set).
(6) Inventors from Japan (US).
(7) Inventors from 27 European Union countries (European).
(8) Other selected inventors from countries other than the US, Japan, and European countries.

Using ANOVA, the following hypothesis was tested:

- PI-inventors funded by NSF received a higher number of patent citations than other groups of inventors.

Figure 7 shows the ANOVA test results. NSF-funded PI-inventors received a significantly higher

Table 13 Highest ranked PI-Inventors' patents (1991–2010)

Technology subfield (US Class: Name)	Number of patents	Highest ranked PI-inventor's patents measured by the number of citations (Rank:[Patent_No.] {Patent_Title} Assignee. Number of Citations)
257: Active solid-state devices (e.g., transistors, solid-state diodes)	3,694	5th: [6487106] {Programmable microelectronic devices and method of forming and programming same} The Arizona Board of Regents. 101
438: Semiconductor device manufacturing: process	2,929	5th: [5772905] {Nanoimprint lithography} The Regents of the University of Minnesota. 65
428: Stock material or miscellaneous articles	2,258	9th: [6114038] {Functionalized nanocrystals and their use in detection systems} Biocrystal, Ltd. 27
977: Nanotechnology	1,353	1st: [6128214] {Molecular wire crossbar memory} Hewlett-Packard Company. 83
427: Coating processes	1,540	1st: [5512131] {Formation of microstamped patterns on surfaces and derivative articles} President and Fellows of Harvard College. 18
424: Drug, bio-affecting and body treating compositions	1,360	17th: [5439686] {Methods for in vivo delivery of substantially water insoluble pharmacologically active agents and compositions useful therefor} Vivorx Pharmaceuticals, Inc. 44
250: Radiant energy	1,463	30th: [5025658] {Compact atomic force microscope} Digital Instruments, Incorporated. 27
435: Chemistry: molecular biology and microbiology	1,209	2nd: [5744305] {Arrays of materials attached to a substrate} Affymetrix, Inc. 169
359: Optics: systems (including communication) and elements	972	16th: [6323989] {Electrophoretic displays using nanoparticles} E Ink Corporation. 64
430: Radiation imagery chemistry: process, composition, or product thereof	977	82nd: [6042998] {Method and apparatus for extending spatial frequencies in photolithography images} The University of New Mexico. 14
524: Synthetic resins or natural rubbers—part of the class 520 series	884	7th: [5883173] {Nanocomposite materials (LAW392)} Exxon Research and Engineering Company. 41
514: Drug, bio-affecting and body treating compositions	853	177th: [5877207] {Synthesis and use of retinoid compounds having negative hormone and/or antagonist activities} Allergan, Inc. 8
252: Compositions	788	1st: [6180029] {Oxygen-containing phosphor powders, methods for making phosphor powders and devices incorporating same} Superior Micro Powders, LLC. 22
356: Optics: measuring and testing	769	25th: [6149868] {Surface enhanced Raman scattering from metal nanoparticle-analyte-noble metal substrate sandwiches} The Penn State Research Foundation. 26
436: Chemistry: analytical and immunological testing	709	3rd: [5744305] {Arrays of materials attached to a substrate} Affymetrix, Inc. 64
422: Chemical apparatus and process disinfecting, deodorizing, preserving, or sterilizing.	647	9th: [5620850] {Molecular recognition at surfaces derivatized with self-assembled monolayers} President and Fellows of Harvard College. 46
385: Optical waveguides	565	3rd: [5841931] {Methods of forming polycrystalline semiconductor waveguides for optoelectronic integrated circuits, and devices formed thereby} Massachusetts Institute of Technology. 23
536: Organic compounds—part of the class 532–570 series	371	1st: [5744305] {Arrays of materials attached to a substrate} Affymetrix, Inc. 79
530: Chemistry: natural resins or derivatives; peptides or proteins; lignins or reaction products thereof	355	27th: [5744305] {Arrays of materials attached to a substrate}00 Affymetrix, Inc. 22
546: Organic compounds—part of the class 532–570 series	127	27th: [5728846] {Benzo[1,2-*g*]-chrom-3-ene and benzo[1,2-*g*]-thiochrom-3-ene derivatives} Allergan, Inc. 9

Table 14 Highest ranked PI-Inventors (2001–2010)

Technology Subfield (US Class: Name)	Number of patents	Highest ranked PI-inventor measured by the number of citations (Rank: [Inventor], Affiliation. Number of Citations)
257: Active solid-state devices (e.g., transistors, solid-state diodes)	3,694	6th: [Yu, Bin], Polytechnic Institute of New York University. 176
438: Semiconductor device manufacturing: process	2,929	4th: [Yu, Bin], Polytechnic Institute of New York University. 164
428: Stock material or miscellaneous articles	2,258	20th: [Bawendi, Moungi G.], Massachusetts Institute of Technology. 37
977: Nanotechnology	1,353	3rd: [Dai, Hongjie], William Rice Marsh Rice University. 111
427: Coating processes	1,540	1st: [Whitesides, George M.], President and Fellows of Harvard College. 57
514: Drug, bio-affecting and body treating compositions	1,360	345th: [Johnson, Alan T.], The University of Pennsylvania. 10
250: Radiant energy	1,463	16th: [Lindsay, Stuart M.], Arizona State University. 80
435: Chemistry: molecular biology and microbiology	1,209	4th: [Pirrung, Michael C.], The University of California at Riverside. 270
359: Optics: systems (including communication) and elements	972	19th: [Jacobson, Joseph M.], Massachusetts Institute of Technology. 76
430: Radiation imagery chemistry: process, composition, or product thereof	977	83rd: [Jacobson, Joseph M.], Massachusetts Institute of Technology. 25
524: Synthetic resins or natural rubbers—part of the class 520 series	884	18th: [Liang, Keng S.], Taiwan and National Synchrotron Radiation Research Center. 41
424: Drug, bio-affecting and body treating compositions	853	11th: [Grinstaff, Mark W.], Boston University. 87
252: Compositions	788	2nd: [Bawendi, Moungi G.], Massachusetts Institute of Technology. 33
356: Optics: measuring and testing	769	21st: [Herzinger, Craig M.], Cornell University. Number of Citations = 44. And 21st: [Woollam, John A.], The University of Nebraska-Lincoln. 44
436: Chemistry: analytical and immunological testing	709	7th: [Pirrung, Michael C.], The University of California at Riverside. 101
422: Chemical apparatus and process disinfecting, deodorizing, preserving, or sterilizing	647	23rd: [Whitesides, George M.], President and Fellows of Harvard College. 61
385: Optical waveguides	565	17th: [Kimerling, Lionel C.], Massachusetts Institute of Technology. 26
536: Organic compounds—part of the class 532–570 series	371	2nd: [Pirrung, Michael C.], The University of California at Riverside. 121
530: Chemistry: natural resins or derivatives; peptides or proteins; lignins or reaction products thereof	355	42nd: [Pirrung, Michael C.], The University of California at Riverside. 29
546: Organic compounds—part of the class 532–570 series	127	31st: [Johnson, Alan T.], The University of Pennsylvania. 13

number of citations in USPTO patents than all other groups, with a mean number of 30.93 citations per PI-inventor. The second tier groups were IBM, TOP10, UC, and US, with mean numbers of citations ranging from 9.04 to 11.65. The country groups including Japan, Europe, and others had the lowest mean numbers of citations, which were less than the mean of the Entire Set. The results supported our hypothesis that PI-inventors received higher numbers of patent citations than other groups of inventors. Also, all results were statistically significant ($P = 0.000$).

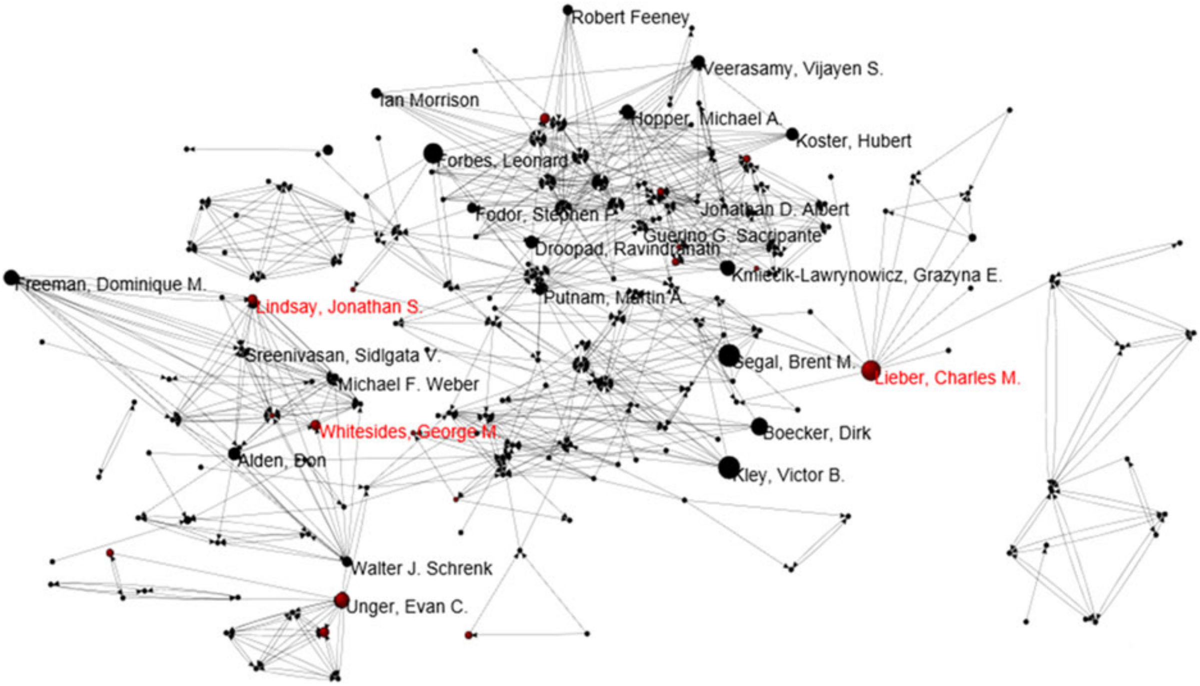

Fig. 6 Citation network of inventors by PageRank

Fig. 7 Comparison of NSF PI-researchers with other groups: the number of citations USPTO Patent authors received in the interval 1991–2010

```
Source       DF          SS      MS       F      P
gROUP         8     2794181  349273  159.79  0.000
Error    308788   674951955    2186
Total    308796   677746137

S = 46.75   R-Sq = 0.41%   R-Sq(adj) = 0.41%

                                 Individual 95% CIs For Mean Based on Pooled StDev
Level            N   Mean  StDev  ---------+---------+---------+---------+
NSF           1887  30.93 113.90                                   (--*-)
IBM           3614  10.21  30.04            (-*-)
TOP10        14076  11.65  87.53               (*)
UC            2497  10.29  35.08            (-*-)
US           96962   9.04  51.08            *)
EntireSet   140855   7.32  44.04          *
Japan        20562   3.43  19.43    (*)
European     20211   1.79   9.03  (*)
Others        8133   2.10   9.99  (-*)
                                  ---------+---------+---------+---------+
                                         8.0      16.0      24.0      32.0

Pooled StDev = 46.75
```

Citations received by PI-researchers

In addition to the nanotechnology patent inventors, we also evaluated the impact of public funding on nanotechnology researchers using our WoS data set. We used "PI-researchers" to represent the authors of scientific publications who were also supported by NSF awards. Again, we compared the number of citations in the WoS papers between PI-researchers and other researcher groups, defined as in the previous section. Using ANOVA, the following hypothesis was tested:

- PI-researchers funded by NSF received a higher number of paper citations than other groups of researchers.

Fig. 8 Comparison of NSF PI-researchers with other groups: the number of citations WoS paper authors received in the interval 1991–2010

```
Source      DF           SS        MS       F      P
Groups       8     89054484  11131811  502.26  0.000
Error   599641  13290105153     22163
Total   599649  13379159638

S = 148.9   R-Sq = 0.67%   R-Sq(adj) = 0.66%

                                   Individual 95% CIs For Mean Based on Pooled StDev
Level           N   Mean  StDev   -------+---------+---------+---------+--
NSF          3615  166.0  693.5                                       (*-)
IBM          1877   53.8  158.8            (*-)
TOP10       33071   27.0  160.2     (*
UC          10097   42.4  233.9         (*
US          85669   31.6  183.2       *
EntireSet  260880   26.2  147.1     (*
Japan       22358   24.2   85.5     *)
European   118429   20.5   94.9    *
Others      63654   15.1   74.5  (*
                                  -------+---------+---------+---------+--
                                        40        80       120       160

Pooled StDev = 148.9
```

Figure 8 shows the ANOVA test results for the 1991–2010 interval. Similar to PI-inventors, the NSF-funded PI-researchers received a significantly higher number of citations as compared with all other groups, with a mean number of 166.0 citations. The second tier groups were IBM and UC, with mean numbers of citations at 53.8 and 42.4, respectively. The third tier groups were the US, top 10, Entire Set, Japan, European, and other country groups, with the mean number of citations ranging from 15.1 to 31.6. The results supported our hypothesis that PI-researchers received higher numbers of paper citations than other groups of researchers. Again, all results were statistically significant ($P = 0.000$).

Conclusion

Nanotechnology continues to be at the top of the wave of discovery and innovation. The 22-year longitudinal evolution of nanotechnology reflected in USPTO patents and WoS scientific publications shows continuous global growth and fast-paced topical changes. Patents and papers increased in (2001–2010) as compared to (1991–2000) by 4.31 and 4.99 times, respectively, while in the two year interval (2011–2012) as compared to (2001–2010) increases are 2.34 and 1.91. This suggests an acceleration of average annual growth in the last couple of years. The progress has been assessed by employing bibliometric analysis, topic analysis, and citation analysis.

The value of NSF-supported NSE research is shown in the larger number of citations in papers and patents for the NSF PIs as compared to leading industry groups and the US average. On average, a PI supported in the interval 1991–2010 has about 31 patent citations and 166 paper citations as compared to the second best group (IBM) with 10 citations in patents and 54 in scientific publication, and to the Entire Set average with 7 citations in patents and 26 citations in scientific publications. The growth of NSF nanotechnology funding in 2001–2010 as compared to 1991–2000 has resulted not only in a significant increase of patents and publications, but also in more diversified technology topics identifiable in patents and publications. Inventors funded by the NSF play important roles in the development of various nanotechnology subfields and in the overall community.

Overall, the US was the leading contributing country for nanotechnology developments in terms of the numbers of patents and scientific publications for the last two decades. However, several Asian countries have been showing exponential growth rates, indicating their increasing contributions to the nanotechnology field. Several EU countries (Italy and Spain) showed a faster pace of growth in the number of scientific publications in the last years.

The dominant industrial and academic institutions in nanotechnology have not changed significantly over the last 20 years. However, several institutions (Micron, Intel, Silverbrook, Nanjing University) have shown significant progress in terms of the number of patents or publications produced.

For future research, we plan to extend this research by incorporating knowledge diffusion models to explore causal relationships between NSE-related public funding and nanotechnology development.

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