

Internationalization and evolution of application areas of an emerging technology: The case of nanotechnology

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Nanotechnology patenting has grown rapidly in recent years as an increasing number of countries are getting into the global nanotechnology race. Using a refined methodology to identify and classify nanotechnology patents, this paper analyses the changing pattern of internationalization of nanotechnology patenting activities from 1976–2004. We show that the dominance of the G5 countries have declined in recent years, not only in terms of quantity, but also in terms of quality as measured by citation indicators. In addition, using a new approach to classifying the intended areas of commercial applications, we show that nanotechnology patenting initially emphasized instrumentation, but exhibited greater diversification to other application areas in recent years. Significant differences in application area specialization are also found among major nanotechnology nations. Moreover, universities are found to play a significant and increasing role in patenting, particularly in US, UK and Canada.

Introduction

Nanotechnology has been heralded as the next major techno-paradigm shift that will have pervasive impacts on production processes, manufacturing and innovation in a wide-range of high-tech sectors. Certain observers have gone as far as touting nanotechnology as the “next industrial revolution”, underlining that this is a technology that will bring about radical changes. Recognizing the tremendous scientific and

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commercial potential for nanotechnology, governments of major nations have accelerated funding for nanotechnology development. LEE et al. (2006) provides a description of the world-wide government funding initiatives to spur nanotech development, beginning with the National Nanotechnology Initiative (NNI) in the USA, which was soon followed by substantial government commitments in Japan, Germany and France, and subsequently spread to more countries like Korea and Taiwan.

A significant current trend in nanotechnology development is the rush to patent (LEMLEY, 2005), with universities and companies making record numbers of applications to patent nanotechnology-related inventions. Several authors have addressed possible concerns that over-patenting may deter innovation and raise licensing costs (MILLER et al., 2005; LEMLEY, 2005). For the purposes of this paper, the surge in patenting activity provides a rich dataset to investigate the nanotechnology phenomenon. Because patents fully disclose the details of the innovation, we are able to apply scientometric methods to study the development of this emerging new technology.

Early scientometric studies in this area have focused on nanoscience, which WOODS et al. (2003) defined as dealing with manipulation and characteristics of small-sized matter, as distinguished from nanotechnology, which is the application of nanoscience to creating new products. Studies on nanoscience relied on bibliometric information found in scientific publications and citations, as reviewed by HULLMAN & MEYER (2003). BRAUN et al. (1997) conducted the pioneering study which analysed the early years of nanoscience by counting the occurrences of the prefix “nano” in the titles of scientific papers published between 1986 and 1995. Later studies by MEYER & PERSSON (1998) and SCHUMMER (2004), among others, have built on this work and generally confirmed a large increase in nanoscience publications in the 1990s.

As nanoscience flourished, technological activities began to take place, giving birth to the burgeoning nanotechnology field (ARNALL & PARR, 2005). COMPANO & HULLMAN (2003) suggest that patents are an appropriate measure of nanotechnology activity, as patents indicate the capacity of research laboratories to transfer research into industrial applications. However, researchers wishing to study nanotechnology patenting faced a challenge due to the lack of consensus on what constitutes nanotechnology. It was only in 2004 that the USPTO created Class 977/Dig.1 as a specific area for nanotechnology patents. Furthermore, full reclassification of relevant patents into Class 977 will be a time-consuming and on-going affair. In the absence of a nanotechnology patent class, several studies have adopted the “nano”-prefix search to identify and analyse nanotechnology patents. These studies have examined issues such as the links between nanotechnology and nanoscience (MEYER, 2000; 2001), development trends (HUANG et al., 2003; 2004) and technology strength (MARINOVA & MCALEER, 2002).

In this paper, we introduce two scientometric refinements to examine the trends and patterns of internationalization of nanotechnology development using USPTO patenting data. Firstly, we refine the keyword-search strategy of previous researchers together with the inclusion of an up-to-date set of Class 977 patents that have been reclassified by the US Patent and Trademark Office (USPTO) as nanotechnology. Analysing the assignee information fields, we trace the internationalization trends of nanotechnology development and attempt to characterise the major nanotechnology countries in the world in terms of both quantity and quality of patenting. Additionally, we have developed a new taxonomy in which each nanotechnology patent may be classified by the intended commercial *application areas* of the patent. This taxonomy allows us not only to examine how the application areas of an emerging technology like nanotechnology evolve over time, but also to understand how different countries that participate in the global nanotechnology race may pursue different specialization strategies in terms of areas of economic emphasis.

Methodology

Identification of nanotechnology patents

Prior empirical work in identifying nanotechnology-related publications and patents primarily consists of using “nano\$” as a basic filter in conjunction with selected keywords. BRAUN et al. (1997) employed this strategy for constructing a database of nanoscience publications, while MEYER (2000; 2001) extended the methodology to identify nanotechnology patents. Recent studies of nanotechnology patenting have similarly used the “nano-” prefix as the basis for defining nanotechnology, as summarized in Table 1.

While this paper follows the same basic keyword search strategy, we introduced a number of refinements in our taxonomic approach. Firstly, although we based our approach on the National Nanotechnology Initiative’s (NNI) definition of nanotechnology as “dimensions of roughly 1 to 100 nanometers”, we adopted a more inclusive coverage approach by allowing for exceptions of scale up to 1000 nanometers when novel properties and behavior of matter resulted from the smaller size (LEE et al., 2006). In identifying such exceptions, patents are accepted into our definition of nanotechnology if they are self-declared to be related to nanotechnology. Additionally, tools and instruments that allow for visualization of atomic structures are covered in our definition.

Table 1. Summary of USPTO-issued nanotechnology patent identification from literature

Study	Period covered	Number of patents identified	Keywords searched	Section searched
HUANG et al. (2003)	Year of grant 1976–2002	77,605	Nano\$ (excluding nanoliter and nanosecond), Selfassembl\$, Self assembl\$, Atomic force microscop\$, Atomic-force-microscop\$, Scanning tunneling microscop\$, Scanning-tunneling-microscop\$, Atomistic simulation, Biomotor, Molecular device, Molecular electronics, Molecular modeling, Molecular motor, Molecular sensor, Molecular simulation, Quantum computing, Quantum dot\$, Quantum effect\$	Full-text
HUANG et al. (2004)	Year of grant 1976–2003	70,039	Same as for HUANG et al. (2003)	Full-text
SAMPAT (2004)	Year of grant 2001–2003	3,748	Same as for HUANG et al. (2003)	Claims
DARBY & ZUCKER (2005)	Year of grant 1981–October 2003	Approx. 3,900-4,000 (numbers estimated from chart in paper)	Nano\$	Title and Abstract
MARINOVA & MCALEER (2002)	Year of application 1975–1998	16,789 for 1995–1998 (figures not provided for earlier years)	Nano\$ (excludes words related to nanoseconds and the chemical compound NaNO)	Full-text
MEYER (2001), HULLMAN & MEYER (2003)	Year of grant 1976–1999	2,624	Nano\$	Title and Abstract
LEE et al. (2006)	Year of grant 1976–2005	4,865	Same as for HUANG et al. (2003), filtered out “nanogram”, “nanometer”, “nanosecond”, “nanoliter”, “nanoampere”, “nanofarad”, “nanomole”, “NaNO”	Abstract

Secondly, we implemented an identification strategy that combines automated keyword searches, manual filtering and UPC code searches. Automated keyword searches were limited to the abstracts rather than the full text to reduce the possibility of identifying patents that may not pertain to nanotechnology. An initial keyword search identified patents with the prefix “nano” and this was later supplemented with searches using keywords used at the National Science Foundation and in a number of other studies (HUANG et al, 2003; 2004; SAMPAT, 2004; LEE et al., 2006).¹ The patents were then filtered for potentially irrelevant patents by searching for measurement-related terms such as “nanogram”, “nanometer”, “nanosecond”, “nanoliter” and others, as well as the chemical compound, “NaNO”.

¹ Atomic force microscop\$, Atomistic simulation, Biomotor, Molecular device, Molecular electronics, Molecular modeling, Molecular motor, Molecular sensor, Molecular simulation, Quantum dot, Quantum computing, Quantum effect, Self assembl\$, Scanning tunneling microscop\$, Nano\$

Finally, we took into account the recent initiative by the USPTO to adopt a new cross-reference art collection Class 977 “Nanotechnology” to classifying existing patents using this new class. Although this is still a work in progress that has covered only a portion of existing patents, we incorporate all patents that have been classified as USPTO Class 977 “Nanotechnology” as at 1st August 2006. This was done in two stages. In the first stage, we added approximately 2,000 patents classified as Class 977 as at March 2006. On August 1st 2006, we searched the USPTO online database and identified an additional 996 patents that had been designated as Class 977 patents since our initial search in March. In completing this exercise, we noted that sizeable numbers of patents that USPTO examiners have classified as being nanotechnology-related have not been caught by the “nano” keyword search. As such, ours is the first study to include this set of nanotechnology patents.

Based on the above refined search strategy, a total of 7,034 patents were identified and extracted for inclusion in our database. The selected patents were downloaded and filtered using a software program, the WizPatent Manager, developed by one of the co-authors. Further manual screening was done for nanotechnology relevancy and irrelevant patents were eliminated.

To verify the accuracy of the keyword-search procedure, a random independent audit was conducted, during which the abstracts of approximately 200 patents were read in detail. The primary auditor is a technical domain specialist who is a multiple patent-holder, and he was supported by two graduate students on attachment to the Nanoscience and Nanotechnology Initiative at the National University of Singapore. The audit showed that this methodology resulted in more accurate identification of nanotechnology-related patents.

Classification of application areas

One characteristic of nanotechnology is that it crosses many product disciplines (LEMLEY, 2005). As such, it is difficult to establish a formal classification system or Art Unit for nanotechnology patents. (BAWA, 2004; SAMPAT, 2004). There is no consensus on how nanotechnology patents can be further classified according to technological subfields. Prior studies have either used the detailed US Patent Classes to describe the technological coverage of nanotechnology patents (HUANG et al., 2003 and 2004) or devised an aggregated sectoral classification based on using the Silverberg/Verspagen concordance table to convert priority classes according to the International Patent Classification (MEYER, 2000; 2001; HULLMAN & MEYER, 2003).

In this paper, we devise a taxonomy that classifies nanotechnology patents into four broad areas of commercial applications: Instrumentation, Chemical Processes & Materials, Medical & Biotechnology and Nanoelectronics (Table 2). These categories represent widely accepted applications of nanotechnology (see HOLISTER (2002) for a

discussion on how the nanotechnology world may be categorized into different technologies and applications). The application areas also correspond broadly to the SIC sectors used by MEYER (2000; 2001) and HULLMAN & MEYER (2003). Where our approach differs is that we do not rely solely on existing technological classes which may not correctly map to the potential application areas for nanotechnology. Rather than strict adherence to the concept of “sector of use”, we have more broadly defined the application areas as having the potential to be developed and produced by different sectors.

Table 2. Classification of nanotechnology application areas

Application area	Example
Nanoelectronics	Nanotube semiconductor devices
Medical And Biotechnology	Drug delivery systems, cosmetics
Chemical Processes And Materials	Nanocatalysts, nanocomposite polymers
Instrumentation, Tools, Metrology, And Standards	Atomic force microscope, nano-positioning device
Other Applications	Water purification and treatment, coatings

The classification of commercial application areas was done using a combination of application-specific keyword searches, technology-specific keyword searches and manual classification. The Appendix lists the keywords used in the classification procedure. The search strategy was later refined to identify instances of words-proximity with stop-words eliminated. Patents which were not classified into any of the 4 broad application areas were designated as belonging to an “Other Applications” category.

Two manual audits were conducted to ensure the accuracy of the keyword-based classification. A first audit manually surveyed 15% of the identified and classified nanotechnology patents and found that 90% of the patents had been correctly classified. A second audit was done on 5% of the recently designated Class 977 patents, and similarly found that 90% were correctly classified.

After identifying and classifying these nanotechnology patents, we extracted and classified various relevant information (such as assignee, inventor location, year of grant) from a full-text, custom-searchable database of USPTO-assigned patents developed and maintained at the National University of Singapore by two of the co-authors.

Overview of nanotechnology patent growth and internationalization trend

Overall growth trend

Our search methodology yielded a total of 7,034 unique nanotechnology patents granted by the USPTO between 1st January 1976 and 31st December 2004. This represents 0.21% of all patents granted by the USPTO during the period. Of these patents, 2,735 were granted prior to the year 2000 and the other 4,299 were granted in

the five-year period 2000–2004. As seen in Table 1, our estimates are comparable to MEYER’s (2001) and HULLMAN & MEYER’s (2003) figure of 2,624 patents for the period 1976–1999, and also to SAMPAT’s (2004) estimate of 3,748 patents for 2001–2003. However, our figure falls far short of HUANG et al (2003; 2004) who found in excess of 70,000 nanotechnology patents and MARINOVA & MCALEER (2002) who arrived at 16,748 patents for the four years between 1995 and 1998. The disparity in the numbers appears to arise from the studies applying the search strategies to different sections of the patent document. Searches that encompass the full-text yield very much higher figures, while searches that are narrowed to titles or abstracts produce more moderate totals.

Figure 1 plots the trend in nanotechnology patents over the years in comparison with the trend in total patents granted by the USPTO. While the broad trends are similar, with a surge in patenting in the late 1990s, and a fall-off in the last 2 years, nanotechnology patenting exhibited a much higher growth rate than overall patenting.

For much of the period pre 1990, very few nanotechnology patents were being granted. It was only around 1990 that significantly large numbers of patents began to be produced. In 1992, over a hundred nanotechnology patents were granted and annual production has continued to rise, peaking at 1,183 patents in 2003.

Table 3. Comparison of nanotechnology vs all patents

	Nanotechnology	All patents
Growth in patents (annual average %)		
Growth rate 1976–1989	24.1	2.4
Growth rate 1990–1999	30.0	6.1
Growth rate 2000–2004	16.5	0.7
Share in total patents (%)		
1976–1989	0.02	–
1990–1999	0.19	–
2000–2004	0.45	–
Concentration ratios		
Share of top 4 inventor countries	88.6	84.8
Share of top 8 inventor countries	97.6	93.3
Share of top 4 assignee countries	86.0	71.5
Share of top 8 assignee countries	88.1	76.6
Share of university owned patents **		
1976–1989	10.8	1.0
1990–1999	14.3	3.3
2000–2004	16.7	3.6

** Figures for all patents proxied by share of US university-owned patents in total US-owned utility patents for 1969–1989, 1990–1999 and 2000–2003. Source: US Patent and Trademark Office, *U.S. Colleges and Universities – Utility Patent Grants, Calendar Years 1969–2003*, downloaded from <http://www.uspto.gov>

The growth rate of nano-technology patents far outstrips that of all patents over 1976–2004, especially in the period 2000–2004, when nanotechnology patents grew at a rate which was over twenty times faster than all patents generally (Table 3). As a result, the share of nanotechnology patents in total patents has grown from 0.19% in the 1990s to 0.45% in 2000–2004.

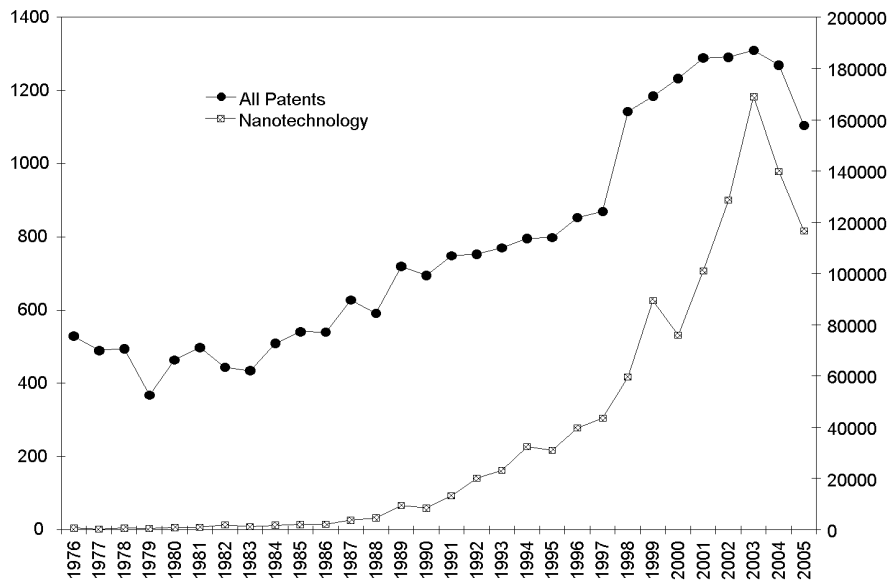


Figure 1. Nanotechnology patents vs total patents

Table 3 additionally highlights several unique characteristics of nanotechnology patents in comparison with other patents. Nanotechnology patents tend to be more highly concentrated geographically, with the top 8 countries with at least one co-inventor resident accounting for 97.6% of the patents, and the top 8 assignee countries owning 88.1% of the patents. Comparatively, across all USPTO patents, the top 8 inventor countries account for 93.3% while the top 8 assignee countries own only 76.6% of patents.

Table 3 also highlights the disproportionately large and increasing shares of nanotechnology patents being owned by universities, a trend that had been observed by previous studies (LEMLEY, 2005). These characteristics will be examined in greater detail in a later section.

Internationalization patterns of nanotechnology patenting

For each patent, we assigned a country of ownership by taking the location of the first named assignee. Additionally, we identified countries of inventorship based on the locations of the inventors named in the patent document. Patents that have co-inventors from different countries may therefore have more than one country of invention. Table 4 lists the top assignee and inventor countries in terms of numbers of nanotechnology patents owned by and invented in each country. Although the ranking of countries differed slightly based on ownership vs. inventorship, the top 12 assignee countries were found to be the same as the top 12 inventor countries.

In most cases, almost all nanotechnology patents owned by the top 10 countries were also invented there, as shown in the fourth column of Table 4. The exception was Netherlands, where 42% of patents were invented overseas. Instances of co-inventorship with foreign inventors were also relatively rare among the top patent owners, with large shares of patents wholly invented locally (fifth column in Table 4). This was especially true of the Asian economies of Japan and Korea. Several countries exhibited relatively higher propensity to co-invent patents with inventors from foreign countries, namely Switzerland (major collaborative partner countries are Germany and France) and Canada (major collaborative partner countries are USA and Sweden).

As the geographic patterns are quite similar for both inventor and assignee countries, the rest of this paper will mostly use the first assignee country to designate the nationality of patents. We will also focus on the top 10 assignee countries, as they account for 95% of the assigned patents in our sample.

The international landscape of nanotechnology patenting has changed considerably in the last 30 years, as illustrated in Table 5. In the period pre-1990, the usual suspects – USA, Japan and Germany – figured prominently, as expected. Not surprisingly, the USA owns the majority of the patents (63% overall) and has maintained its position of leadership over the years. However, from a 70% share in the 1970s and 1980s, the USA's dominance has been eroded slightly since 1990 with the emergence of nanotechnology centres in other countries. In the 1990's, Japan became a prominent location for nanotechnology patenting and accounted for 22% of patents granted. Active patenting by L'Oreal meant that France also exhibited a strong showing in this decade. The most recent period, 2000–2004, witnessed the emergence of several additional economies that began producing nanotechnology patents in substantial numbers. In particular, starting with negligibly small numbers prior to 2000, nanotechnology patenting has taken off with great rapidity in Korea, Australia and Taiwan. In the last 5 years, these economies had leap-frogged a number of traditionally prolific European countries in terms of total nanotechnology patents owned, with Korea replacing France as the fourth largest nanotechnology-inventing nation during that period, while Australia and Taiwan overtook UK.

Table 4. Top assignee and inventor countries for nanotechnology patents

	Assigned					Invented			
	A	B	C	D	E	F	G	H	I
USA	4229	60.1	63.3	95.8	88.9	4503	62.6	64.0	90.0
Japan	1029	14.6	15.4	97.2	94.8	1057	14.7	15.0	94.6
Germany	288	4.1	4.3	89.6	83.7	407	5.7	5.8	63.4
France	197	2.8	3.0	97.0	90.4	263	3.7	3.7	72.6
Korea	143	2.0	2.1	97.9	95.8	155	2.2	2.2	90.3
Canada	132	1.9	2.0	93.9	74.2	185	2.6	2.6	77.0
Australia	93	1.3	1.4	100.0	90.3	106	1.5	1.5	87.7
Taiwan	86	1.2	1.3	94.2	87.2	100	1.4	1.4	81.0
UK	85	1.2	1.3	85.9	71.8	170	2.4	2.4	42.9
Netherlands	64	0.9	1.0	57.8	50.0	62	0.9	0.9	59.7
Switzerland	52	0.7	0.8	82.7	53.8	122	1.7	1.7	35.2
Israel	36	0.5	0.5	91.7	77.8	69	1.0	1.0	47.8
Other Europe	181	2.6	2.7						
Other Asia	44	0.6	0.7						
Others	17	0.2	0.3						
Unassigned	358	5.1							
Total assigned nanotech patents	6676								
Total nanotech patents	7034					7034			
Total patent count for top 12 inventor country						7199			

A: # of patents; B: % share of total nanotech patents; C: % share of assigned nanotech patents; D: % that are locally invented; E: % that are wholly locally invented; F: # of patents; G: % share of top 12 total patent counts; H: % share of total nanotech patents; I: % that is locally assigned

Table 5. Internationalization trends in nanotechnology patents ownership

	Share in assigned nanotechnology patents				Revealed patent advantage for nanotechnology patents		
	1976–1989	1990–1999	2000–2004	Overall	1976–1989	1990–1999	2000–2004
USA	69.9	63.0	63.3	63.3	0.386	0.317	0.301
Japan	9.7	21.9	11.9	15.4	-0.268	0.096	-0.458
Germany	5.6	3.4	4.8	4.3	-0.065	-0.435	-0.184
France	1.5	3.8	2.5	3.0	-0.485	0.466	0.211
Korea	0.0	0.5	3.2	2.1	-1.000	-0.675	0.408
Canada	0.5	1.8	2.2	2.0	-0.586	0.362	0.341
Australia	0.5	0.6	1.9	1.4	0.552	0.617	0.920
Taiwan	0.0	0.3	1.9	1.3	-1.000	-0.702	-0.194
UK	3.1	1.1	1.3	1.3	0.349	-0.415	-0.042
Netherlands	3.6	0.5	1.1	1.0	0.963	-0.198	0.150
Other Europe	5.6	2.6	3.9	3.5			
Other Asia	0.0	0.1	1.0	0.7			
Others	0.0	0.5	1.0	0.8			
Total assigned nanotech patents	196	2381	4099	6676			

Table 5 also reports the Revealed Patent Advantage (RPA) for nanotechnology patents among the top 10 assignee countries. RPA has been proposed by GRUPP (1994) as a measure of international patent specialisation, based on a similar concept of Revealed Comparative Advantage (RCA) originally applied in the context of

international trade specialisation. Unlike RCA, RPA had the added advantage of being symmetrical around the origin (zero), and is defined as follows:

$$RPA_{i,j} = (RTA^2 - 1)/(RTA^2 + 1) * 100, \text{ where } RTA = \frac{X_{i,j} / \sum_i X_{i,j}}{\sum_j X_{i,j} / \sum_i \sum_j X_{i,j}}$$

$X_{i,j}$ is the number of patents in technology class i in country j . In our case, i refers to nanotechnology.

RTA (Revealed Technological Advantage) is analogous to the RCA for trade data. The RTA index contains a comparison of national patent structure (numerator) with the global patent structure (the denominator). The adjustments to the RTA to derive the RPA render the measure symmetrical, ranging from -1 to 1 with zero representing zero advantage. Positive values represent comparative advantage in patenting for nanotechnology and negative values represent comparative disadvantage.

From Table 5, it is apparent that large shares in total nanotechnology patents do not always translate to comparative advantage. Japan and Germany are at comparative disadvantage in nanotechnology despite owning the second and third largest number of patents. The USA has consistently enjoyed a comparative advantage, although this has decreased slightly over the years in tandem with its decreased share in total patents. In the last 5 years, it is the newly emerging nanotechnology nations that have enjoyed the strongest comparative advantage, with Australia leading the way, followed by Korea. While Taiwan has increased its number of nanotechnology patents substantially, it still suffers a comparative disadvantage in this field.

National strengths in nanotechnology adjusted for patent quality

While patent counts provide an idea of how nanotechnology development is spread across nations, they do not tell us about the quality of the patents granted to different nations. Using the average number of patent citations received as a proxy indicator of the quality of patents, Table 6 shows that American nanotechnology patents have received the highest average number of citations per patents, whereas patents in France and Germany had relatively lower average citations, belying their rankings among the top nanotechnology nations. On the other hand, two lower-ranked assignee countries, Canada and Australia, were found to have patents that were more often-cited.

Table 6 also reports two different derived measures of the relative strengths of nations in terms of patent quality based on citations analysis. The Relative Citation Index (RCI) is computed as the ratio of each nation's share in total citations received to its share in the world's total patents. A RCI value above 1 indicates that a nation's patents attracted a high share of citations relative to that nation's share in nanotechnology patents. In the period 2000–2004, only USA, Canada and Australia

achieved RCI values above 1. RCI has increased since 2000 for 6 nations, declined for 3 nations and remained unchanged for the USA. Canada and Taiwan has enjoyed the largest improvement in their RCI values.

Table 6. Relative quality and impact of nanotechnology patents of top 10 assignee countries

	Average citations received per patent		Relative Citation Index		High Impact Index	
	1976–1999	2000–2004	1976–1999	2000–2004	1976–1999	2000–2004
USA	14.65	2.11	1.19	1.18	1.36	1.17
Japan	9.73	1.77	0.79	0.99	0.33	0.76
Germany	7.75	1.24	0.63	0.69	0.21	0.42
France	6.83	0.89	0.56	0.50	0.00	0.00
Korea	9.75	1.26	0.79	0.70	1.64	1.26
Canada	7.93	1.94	0.64	1.09	0.46	1.86
Australia	15.38	1.83	1.25	1.02	2.46	1.08
Taiwan	4.00	1.61	0.33	0.90	0.00	0.52
UK	9.72	0.64	0.79	0.36	0.61	0.00
Netherlands	3.33	0.76	0.27	0.42	0.00	0.51
Overall	12.58	1.85	–	–	–	–

The High Impact Index(HII) seeks to measure the extent to which nations are under- or over-represented in terms of high-impact patents, defined as those that are among the top 5% most frequently cited among all nanotechnology patents issued in any given year. These top 5% most cited patents are identified for each issue year and pooled over the full set of patents, to avoid truncation biases. The High Impact Index for a country is computed as the share of that country in the world's top 5% most-cited patents relative to its share in world's total patents.

Relative to their contribution to nanotechnology patenting, Canada, Australia, Korea and the USA have the largest share of high-impact patents, as seen in Table 6. Canadian patents have greatly improved in terms of impact, with HII jumping from 0.46 pre-2000 to 1.86 for the period 2000–2004. While Japan and Germany achieved improving levels of their HII, both have HII values below 1.0. France, while a major nanotechnology-producing nation, has no influential patents at all.

The above analysis shows that leadership in nanotechnology changes when we factor in patent quality. While the G5 nations continue to dominate in terms of number of nanotechnology patents owned, it is the smaller economies like Korea, Taiwan, Australia and Canada that have greater share of the highest-impact patents relative to their patent portfolio.

Applications areas of nanotechnology patents

Previous studies by MEYER (2000; 2001) and HULLMAN & MEYER (2003) have categorised nanotechnology patents according to sectors using the IPC-ISIC concordance scheme. As explained previously, we developed our own classification of

nanotechnology patents into one or more of 4 potential areas of commercial applications. Patents that could not be classified into any of these categories were assigned to the category “Other Applications”, making a total of 5 application areas. By using commercial application areas, our taxonomy allows for the wide applicability of nanotechnology to multiple products and industries, as concluded by BAWA (2004). It also acknowledges that nanotechnology draws on contributions from various fields of science and technology (MEYER & PERSSON, 1998) and as such, cuts across multiple technology classes.

From Figure 2, the share of patents that are intended to be applied commercially to the area of Instrumentation has shrunk from 25% pre-2000 to 12% for patents issues between 2000 and 2004. This trend is typical of the development path of most instrumentation-driven fields (ROSENBERG, 1992) when instrumentation-based inventions are adapted for use in other fields. A similar pattern was observed by HULLMAN & MEYER (2003) in their analysis of US nano-patents.

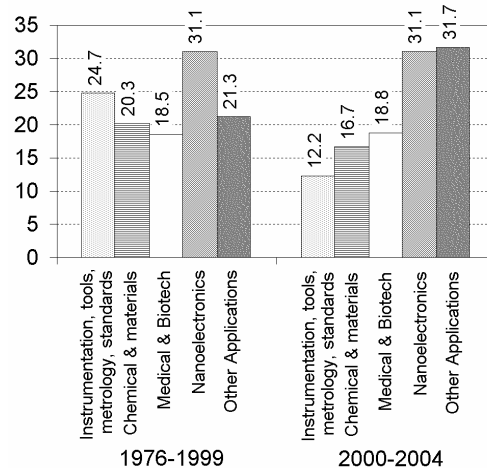


Figure 2. Trend in nanotechnology application areas

Note: A disproportionately large proportion of Class 977 patents were classified as patents with Instrumentation applications, suggesting a probable bias in the Class 977 classification towards such patents

Another notable trend is the increase in the share of patents that are classified in the “Other Applications” category, rising from 21.3% prior to 2000 to 31.7% in 2000–2004. This suggests that nanotechnology is increasingly being applied commercially in areas beyond the major categories of Instrumentation, Medical & Biotechnology, Chemical Processes and Materials and Nanoelectronics. A future refinement of our taxonomy would attempt to provide further classifications of these additional areas of application.

Table 7 summarises the key application areas that each of the top 10 assignee countries specialises in. The Herfindahl Index of concentration has also been computed to provide an indication of the degree of application concentration in the major nanotechnology nations. We observe that Japan and France own the most highly specialised patents, with Japan being highly focused on Nanoelectronics (46.2%) and Instrumentation (39.4%) while French patents are heavily concentrated in the Medical and Biotechnology area (56.9%). In contrast, patents owned by the USA and Germany are more diversified across all the application areas.

Table 7. Summary of key area of specialisation in top 10 assignee country

	Application area	Herfindahl Index of Specialisation
USA	Nanoelectronics	0.372
Japan	Nanoelectronics, Instrumentation	0.584
Germany	Nanoelectronics, Chemical Processes & Materials	0.341
France	Medical & Biotechnology	0.582
Korea	Nanoelectronics	0.431
Canada	Medical & Biotechnology	0.404
Australia	Nanoelectronics, Medical & Biotechnology	0.421
Taiwan	Nanoelectronics	0.581
UK	Medical & Biotechnology	0.442
Netherlands	Chemical Processes & Materials, Nanoelectronics	0.390

Table 8 shows the Relative Citation Index and High Impact Index of each nation with respect to each of the 4 main application areas. The USA has generally the highest quality patents and is the only country with RCI values above 1 in all the application areas. In the Instrumentation area, patents from Australia, Canada and UK achieved the highest RCI values, while in the Medical & Biotechnology area, apart from the USA, Australian and Japanese patents had the highest RCI values.

Table 8. Quality of nanotechnology patents in top 10 assignee countries by area of application

	Relative Citation Index				High Impact Index			
	Instr	Chem	Med	Nanoel	Instr	Chem	Med	Nanoel
USA	1.10	1.13	1.09	1.14	1.22	1.22	1.31	1.28
Japan	0.85	0.58	1.00	0.76	0.44	0.36	0.00	0.43
Germany	0.32	0.67	0.44	0.48	0.00	0.62	0.00	0.21
France	0.18	0.35	0.55	0.23	0.00	0.00	0.00	0.00
Korea	0.15	0.41	0.08	0.36	0.00	0.73	0.00	0.80
Canada	1.52	0.62	0.61	0.50	4.46	0.00	0.86	2.23
Australia	2.23	0.45	2.08	0.51	11.16	0.00	2.73	0.74
Taiwan	0.15	0.47	0.00	0.23	0.00	0.00	0.00	0.39
UK	1.26	0.29	0.66	0.56	0.00	0.00	0.59	0.00
Netherlands	0.49	0.38	0.12	0.13	0.00	0.00	0.00	0.00

Instr: Instrumentation, Tools, Metrology, Standards

Chem: Chemical Processes & Materials

Med: Medical & Biotech

Nanoel: Nanoelectronics

In terms of the High Impact Index, the USA is similarly the only economy with values above 1 in all 4 application areas. While Canada and Australia had only a small number of Instrumentation patents, many of these patents are highly cited, resulting in very high HII values of 4.5 for Canada and 11.2 for Australia. Nanoelectronics patents from Canada are also highly impactful, while Australia's specialisation in Medical & Biotechnology nano-patents is matched by a high HII value.

Other than the case of Australia's high HII in the Medical & Biotechnology area, there is no obvious correlation between a country's area of specialisation and the quality of its patents in that area. For RCI, we do observe some correlation with areas of specialization: For example, in France, the RCI value is highest for its Medical & Biotechnology patents; similarly for Germany, the highest RCI values are for its Chemical Processes & Materials and Nanoelectronics patents. On the other hand, in Australia and Canada, RCI values in the specialised areas are lower than in areas where the numbers of patents held are much lower.

In Tables 9 and 10, we examine how nanotechnology patents cite each other across the different areas of applications. The citations analysis is summarised into two Indices: the Generality Index examining citations received and the Originality Index examining citations made.

Table 9. Generality Index for nanotechnology patents

	Overall	Instrumentation, tools, metrology, standards	Chemical Processes & Materials	Medical & Biotechnology	Nanoelectronics
USA	0.677	0.268	0.721	0.578	0.566
Japan	0.421	0.225	0.615	0.376	0.446
Germany	0.700	0.175	0.633	0.614	0.595
France	0.587	0.222	0.629	0.434	0.286
Korea	0.658	0.551	0.661	0.000	0.555
Canada	0.730	0.155	0.616	0.436	0.575
Australia	0.577	0.258	0.444	0.278	0.571
Taiwan	0.642	0.000	0.594	0.000	0.523
UK	0.693	0.181	0.000	0.275	0.556
Netherlands	0.728	0.139	0.444	0.480	0.139
Other Europe	0.676	0.624	0.511	0.542	0.488
Other Asia	0.725	0.000	0.640	0.000	0.653
Others	0.499	0.000	0.375	0.000	0.444
Overall	0.654	0.257	0.714	0.578	0.547

The Generality Index, as developed by TRAJTENBERG et al. (1997), is a measure of the extent to which the technology embodied in a patent can be regarded as "basic" in the sense that follow-up technical advances are spread across different fields, rather than being concentrated in a small number of them. If a patent is cited by subsequent patents that belong to wide range of fields, the Generality Index is high; whereas the Generality Index would be low if citations received are concentrated in only a few fields.

Table 10. Originality Index for nanotechnology patents

	Overall	Instrumentation, tools, metrology, standards	Chemical Processes & Materials	Medical & Biotechnology	Nanoelectronics
USA	0.644	0.266	0.624	0.541	0.525
Japan	0.418	0.259	0.600	0.542	0.386
Germany	0.658	0.245	0.672	0.109	0.442
France	0.678	0.408	0.570	0.354	0.235
Korea	0.625	0.104	0.560	0.000	0.413
Canada	0.705	0.453	0.630	0.113	0.557
Australia	0.703	0.000	0.500	0.000	0.667
Taiwan	0.675	0.365	0.463	0.667	0.561
UK	0.731	0.311	0.444	0.215	0.000
Netherlands	0.659	0.500	0.367	0.286	0.531
Other Europe	0.692	0.314	0.597	0.394	0.337
Other Asia	0.671	0.500	0.631	0.000	0.397
Others	0.704	0.271	0.640	0.554	0.469
Overall	0.638	0.266	0.646	0.529	0.504

In our context, we examine the generality of nanotechnology patents in terms of the application areas of the subsequent nanotechnology patents that reference the originating patents.

$$\text{Generality Index} = 1 - \sum_j s_{ij}^2,$$

where s_{ij} is the share of citations received by patent i that belongs to application area j .

From Table 9, we find that interestingly, Instrumentation patents have the lowest Generality score of the 4 application areas. This means that Instrumentation nano-patents tend to be cited only by patents within one or two application areas and not across all 4 application areas. Detailed analysis reveals that 80% of citations received by Instrumentation patents are from patents that are also in the Instrumentation area. On the other hand, Chemical Processes and Materials patents influence subsequent patents in all the application areas. Cross-country analysis of the generality scores also yield several interesting observations. For example, while Japan has a high degree of specialisation in Nanoelectronics patents, its generality score in this area is relatively low, especially in comparison to Germany, another country with strong specialisation in Nanoelectronics. This suggests that Japan's nanoelectronics patents may be technologically more "applied" and less "basic".

On the flip side of the Generality Index is the Originality Index, measuring the extent to which patents make reference to patents across a wide range of fields. Patents that cite patents from a narrow set of fields would have low originality while patents with citations to patents in a large range of fields would have high originality scores.

$$\text{Originality Index} = 1 - \sum_j s_{ij}^2,$$

where s_{ij} is the share of citations made by patent i that belongs to application area j .

In Table 10, we observe that the patents with the highest originality score are in the Chemical Processes and Materials area, while the Instrumentation patents have the lowest originality scores. This is similar to the results for the Generality Index, with Instrumentation patents drawing primarily on patents within the same application area, while Chemical Processes and Materials patents cite patents from across all application areas.

The possible influence of institutional ownership

We had earlier observed that an unusually high proportion of patents in nanotechnology are assigned to universities and institutes of higher education. In this, parallels may be drawn between nanotechnology and another emerging technological field, biotechnology. Several papers have noted the similarity between the nanotechnology and biotechnology fields (e. g. DARBY & ZUCKER, 2003; DARBY & ZUCKER, 2004; LEMLEY, 2005). They are both enabling technologies which result in industries experiencing metamorphic growth, and have a relatively heavy reliance on university research. LEMLEY (2005) reports that at least 12% of nanotechnology patents are owned by universities, about a dozen times higher than the proportion of university patents in general. According to figures from Adelman and DeAngelis' biotechnology patent database, university and government patenting together accounted for 15% of biotechnology patents issued in 1990, increasing to 20% in 1994, and has remained at this level ever since (ADELMAN & DEANGELIS, 2007).

One feature of the growth of biotechnology patents is the relatively larger role played by public science in the earlier years of the field's development. Between 1990 and 1994, university- and government-owned biotechnology patents grew at around 30%, while firm-owned patents grew substantially slower, at around 20%. However, from 1994, the annual number of biotechnology patents issued to corporations increased dramatically, and since then they have grown at approximately the same rate as university- and government-owned biotechnology patents.² This seems to imply that in the earlier years of biotechnology research, universities and public research institutes played a more leading role compared to latter years, and points to the need for biotechnology firms to leverage on basic research more typically done in universities and public research laboratories.

In Figure 3, we observe that the role of universities and public sector institutions in nanotechnology patenting continues to be very strong. In the last five years 2000–2004, the share of university owned patents has increased over previous years (Figure 3). Although nanotechnology is perhaps 15–20 years younger than biotechnology, it appears to follow a similar growth trajectory to the early years of biotechnology.

² Calculated from data reported in ADELMAN & DEANGELIS (2007)

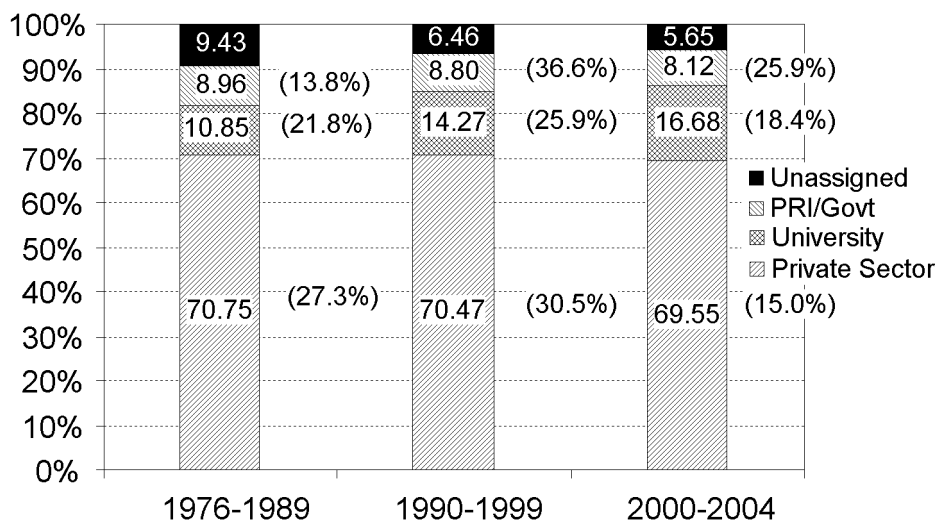


Figure 3. Ownership of nanotechnology patents

Note: Figures in parentheses are annual average growth rates for the period

As of the end of 2004, the nanotechnology industry did not seem to have matured to the point where private sector patenting growth exceeded that of university patents. It seems likely that this pattern will emerge in nanotechnology patenting in the future. Early indications of this trend can be found in prior bibliometric research on journal articles, which shows that firms enter industries such as nanotechnology after university scientists publish research having significant scientific breakthroughs (LEMLEY, 2005; DARBY & ZUCKER, 2003).

While there is overall a high degree of university and public sector ownership, there are significant differences between countries in terms of institutional ownership patterns. Table 11 compares public-sector ownership of nanotechnology patents in the top 10 assignee countries. The countries may be divided into four distinct groups. The first group comprises USA, Canada and UK, three developed nations in the Anglo-Saxon tradition. University ownership of nanotechnology patents is particularly high in this group due a strong tradition of academia-led scientific innovation, while public-sector ownership has reduced over time and is now the lowest among all the top nanotechnology centres. The second group of countries are the two European nations, Germany and France. The level of university ownership is low, but relatively high proportions of patents are owned by the public sector, reflecting the influence of government initiated R&D in mission-oriented public research institutions. The third group includes three developed nations, Japan, Australia and the Netherlands, where

both university and public sector ownership levels are low. In these economies, the private sector dominates nanotechnology invention, accounting for around 90% of patents. The last group comprises the two East Asia NIEs, Korea and Taiwan. These two economies have followed a development path where innovation is driven by government sponsored research in either large public research institutes (ITRI in the case of Taiwan) or in public universities (KAIST in the case of Korea). Correspondingly, the public sector owns a disproportionately high share of nanotechnology patents.

Table 11. Trends in non-private sector ownership of nanotechnology patents

Assignee country	% owned by universities			% owned by government / PRIs		
	1976–1989	1990–1999	2000–2004	1976–1989	1990–1999	2000–2004
USA	16.8	21.4	23.4	6.6	9.1	5.6
Canada	0.0	31.0	16.9	0.0	4.8	3.4
UK	0.0	19.2	18.9	33.3	11.5	7.5
Germany	0.0	2.4	1.0	0.0	12.2	13.3
France	0.0	0.0	3.8	100.0	24.4	20.2
Japan	0.0	0.6	2.7	15.8	4.8	8.0
Australia	0.0	6.7	5.2	100.0	6.7	5.2
Netherlands	0.0	9.1	4.3	0.0	9.1	8.7
Korea		0.0	3.1		66.7	28.2
Taiwan		0.0	5.1		100.0	45.6
Overall	10.8	14.3	16.7	9.0	8.8	8.1

Table 12 and Table 13 show that university patents are of higher quality and have greater impact than private sector patents, especially in the earlier years. In the period pre-2000, average citations are higher for university patents than for private sector patents. However, for patents issued in the period 2000–2004, the average citations received did not significantly differ between universities and private sector corporations. In Table 13, we see that close to 9% of university patents in the 1970s and 1980s were considered high-impact patents, compared to only 2% of private sector patents. By the 1990s, the gap was almost entirely erased, with both private sector corporations and universities having around 5% to 6% of their patents counted among the high-impact pool. In the latest period, 2000–2004, 5.7% of university patents are high impact, marginally higher than 5.0% for private sector patents. Taken together, these findings suggest that in terms of patent quality and impact, private sector companies have almost caught up with the universities since the 1990s. In contrast, the relative quality of nanopatents coming out of public sector research institutes appears to have dropped dramatically over time: while over 10% of their patents before 1990 were among the most highly cited, this had dropped to 1.8% in the 1990s and 1.4% in the first half of the 2000s (Table 14); in terms of average citations received, they had also scored significantly lower compared to universities since the 1990s.

Table 12. Average citations received per patent by assignee type

	1976–1989	1990–1999	2000–2004	Overall
Private sector	21.49	11.76	1.90	6.06
University	34.35	13.98	2.09	6.65
Public sector	19.37	7.82	1.27	4.32
F stat	2.536*	10.724**	4.617**	7.255**
	(p=0.082)	(p=0.000)	(p=0.010)	(p=0.000)
t-stat for difference between university and private sector	2.139**	2.146**	1.012	1.323
	(p=0.034)	(p=0.032)	(p=0.307)	(p=0.186)
t-stat for difference between university and public sector	1.854*	5.455**	3.651**	4.410**
	(p=0.071)	(p=0.000)	(p=0.000)	(p=0.000)

Table 13. Share in top 5% most cited nanotechnology patents by assignee type

Assignee Type	% of patents that are among top 5% most cited		
	1976–1989	1990–1999	2000–2004
Private Sector	2.0	5.4	5.0
University	8.7	5.8	5.7
Public Sector	10.5	1.8	1.4

Chi squared = 14.1*** (p=0.000)

In Table 14, we analyze the pattern of institutional ownership in the different areas of applications. Across all applications except Nanoelectronics, the share of university owned patents has increased since 2000. The importance of universities is most evident for patents in the area of Chemical Processes & Materials and Medical and Biotechnology, with close to 20% of patents being university-owned. Government sector ownership is also higher than average for these two applications.

Table 14. Institutional ownership by application area

	Private sector	University	PRI/Govt	Unassigned	Total
1976–1999					
Instrumentation	77.29	12.33	5.71	4.66	100.00
Chemical & Materials	68.06	16.33	10.16	5.44	100.00
Medical & Biotechnology	65.02	16.21	11.66	7.11	100.00
Nanoelectronics	68.22	16.94	7.83	7.01	100.00
Other Applications	69.41	11.09	9.75	9.75	100.00
2000–2004					
Instrumentation	74.33	14.37	6.70	4.60	100.00
Chemical & Materials	61.09	22.59	10.88	5.44	100.00
Medical & Biotechnology	66.95	20.32	6.61	6.12	100.00
Nanoelectronics	73.58	14.42	7.32	4.68	100.00
Other Applications	68.64	15.83	8.83	6.71	100.00
Overall					
Instrumentation	75.99	13.23	6.15	4.63	100.00
Chemical & Materials	64.12	19.87	10.57	5.44	100.00
Medical & Biotechnology	66.21	18.75	8.54	6.50	100.00
Nanoelectronics	71.48	15.41	7.52	5.59	100.00
Other Applications	68.87	14.39	9.10	7.63	100.00

This is further borne out by an analysis of the top patent owning organizations in each of the application areas. Three of the top 10 patent owners in the Medical and Biotechnology area, and four of the top 10 in the Chemical Processes and Materials area, are universities/public sector organizations. For both application areas, the University of California is the 2nd largest patent owner. In comparison, the University of California is the fourth largest patent owner and the only non-corporate to feature in the top 10 Nanoelectronics organizations. There are two universities among the top 10 for the Instrumentation area, ranking 5th and 8th.

Conclusion

Based on our analysis using USPTO patent data, the evolutionary dynamics of nanotechnology as a major emerging technology appears to share three broadly similar characteristics with an earlier major science-based technology – biotechnology – but with some interesting variations as well. Firstly, like biotechnology, nanotechnology patenting started with a strong concentration in the US followed by other leading G5 nations. Over time, however, the dominance by G5 has declined, while others have caught up. In the case of nanotechnology, the catching up appears to have been more widespread earlier than in the case of biotechnology; moreover, it appears to be not just in terms of quantity of patenting, but also in terms of quality as measured by various citation measures.

Secondly, just as biotechnology initially focused on the “tools of invention” (DARBY & ZUCKER, 2003), the intended application areas of nano-technological innovation initially focused on instrumentation, before shifting to other applications, with increasing proliferation in various not-easily classified niche applications in later stages. In the case of nanotechnology, we have found significant differences in specialization pattern among the leading patenting nations. While similar analyses appear not to have been done in the case of biotechnology, it is likely that such application specialization across countries may be found as well (e.g. Scandinavian countries appear to have more emphasis on application in industrial process and food production).

Finally, similar to what happened in biotechnology, university and public sector institutions played a much more significant role in nanotechnology than in general patenting. However, while the role of public sector has declined slightly over time, the role of university is still on the increase in nano-patenting, whereas the share of university patenting has stabilized in the case of biotechnology in recent years. Notwithstanding this, the quality of university patents (as measured by citations) relative to private sector did appear to have narrowed over time, suggesting that the continuing quantitative expansion of university patenting in recent years may be at the expense of quality.

*

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References

- ADELMAN, D. E., DEANGELIS, K. L. (2007), Patent metrics: The mismeasure of innovation in the biotech patent debate, *Texas Law Review*, forthcoming.
- ARNALL, A., PARR, D. (2005), Moving the nanoscience and technology debate forwards: short-term impacts, long-term uncertainty and the social constitution, *Technology in Society*, 27 : 23–38.
- BAWA, R. (2004), Nanotechnology patenting in the US, *Nanotechnology Law and Business*, 1 : 31–50.
- BRAUN, T., SCHUBERT, A., ZSINDELY, S. (1997), Nanoscience and nanotechnology on the balance, *Scientometrics*, 38 (2) : 321–325.
- COMPANO, R., HULLMAN, A. (2002), Forecasting the development of nanotechnology with the help of science and technology indicators, *Nanotechnology*, 13 (3) : 243–247.
- DARBY, M. R., ZUCKER, L. G. (2003), Grilichesian breakthroughs: Inventions of methods of inventing and firm entry in nanotechnology, *National Bureau of Economic Research Working Paper* No. 9825.
- DARBY, M. R., ZUCKER, L. G. (2004), Formation and transformation of industries: Nanotechnology, chapter 2 in *Nanoscience and Nanotechnology: Opportunities and Challenges in California*, Sacramento, CA: California Council on Science and Technology. Downloaded from <http://www.ccst.us/ccst/pubs/nano/NanoReport.pdf>
- GRUPP, H. (1994), The measurement of technical performance of innovations by technometrics and its impact on established technology indicators, *Research Policy*, 23 : 175–193.
- HOLISTER, P. (2002), Nanotech: the tiny revolution. *CMP Cientifica*.
- HUANG, Z., CHEN, H., CHEN, Z. K., ROCO, M. C. (2004), International nanotechnology development in 2003: Country, institution and technology field analysis based on USPTO patent database, *Journal of Nanoparticle Research*, 6 : 325–354.
- HUANG, Z., CHEN, H., YIP, A., NG, G., GUO, F., CHEN, Z. K., ROCO, M. C. (2003), Longitudinal patent analysis for nanoscale science and engineering: Country, institution and technology field, *Journal of Nanoparticle Research*, 5 : 333–363.
- HULLMAN, A., MEYER, M. (2003), Publications and patents in nanotechnology: An overview of previous studies and the state of the art, *Scientometrics*, 58 (3) : 507–527.
- LEE, L. L., CHAN, C. K., NGAIM, M., RAMAKRISHNA, S. (2006), Nanotechnology patent landscape 2006, *Nano*, 1 (2) : 101–113.
- LEMLEY, M. A. (2005), Patenting nanotechnology, *Stanford Law Review*, 61 : 601–630.
- MARINOVA, D., MCALEER, M. (2003) Nanotechnology strength indicators: International rankings based on US patents. *Nanotechnology*, 14 : R1–R7.
- MEYER, M. (2000), Patent citations in a novel field of technology: What can they tell about interactions of emerging communities of science and technology? *Scientometrics*, 48 : 151–178.
- MEYER, M. (2001), Patent citation analysis in a novel field of technology: An exploration of nano-science and nano-technology. *Scientometrics*, 51 : 163–183.
- MEYER, M., PERSSON, O. (1998), Nanotechnology: Interdisciplinarity, patterns of collaboration and differences in application, *Scientometrics*, 42 : 195–205.
- MILLER, J. C., SERRATO, R., REPRESAS-CARDENAS, J. M., KUNDAHL, G. (2005), *The Handbook Of Nanotechnology: Business, Policy, And Intellectual Property Law 224*, John Wiley: New York.
- ROSENBERG, N. (1992) Scientific instrumentation and university research, *Research Policy*, 21 : 381–390.
- SAMPAT, B. N., (2004) *Examining Patent Examination: An Analysis of Examiner and Applicant Generated Prior Art*, Haas Business School Working Paper, downloaded from <http://faculty.haas.berkeley.edu/wakeman/ba297tspring05/Sampat.pdf>

- SCHUMMER, J. (2004). Multidisciplinarity, interdisciplinarity, and patterns of research collaboration in nanoscience and nanotechnology, *Scientometrics*, 59 (3) : 425–465
- TRAJTENBERG, M., JAFFE, A., HENDERSON, R (1997). University versus corporate patents: A window on the basicness of invention, *Economics of Innovation and New Technology*, 5 (1) : 19–50.

Appendix

Search terms for classifying application areas

Nanoelectronics

nanoelectronic, nano-electronic, quantum dot, silicon, magnet, conduction, conductor, semiconduct, electric, wire, lithography, resistance, current, transistor, printed circuit, PCB, photonic, light emitting diode, conductivity, capacitor, transistor, inductor, dopant, diode, rectifier, impedance

Medical and Biotechnology

drug delivery, drug, diagnostic, medical, medicine, biological, nanoemulsion, cosmetic, bio, pharma, nanoshell, nanopor, nanocapsule, toxicity, nucleic, nucleus, antibacterial, antimicrobial, DNA, therapeutic, cell, protein, skin, immun\$ (to include immunogenic and immune, immunity), antigen, antibiotic, vaccine, intravenous, oral, intranasal, disease, disorder, implant, biomaterial, infection, topical, gene, genome, virus, vector, peptide, in-vivo

Chemical Processes and Materials

zeolite, chemical, synthesis, nanofab, nano-fab, petrol, catalyst, battery, batteries, solvent, polymer, colloid, etch, acid, oxidation, reduction, sol-gel, plasma, pyrolysis, precipitation, decomposition, electrophoresis

Instrumentation, Tools, Metrology and Standards

microelectromechanical, quantum dot, metrology, instrument, tool, calibrat\$, standard, probe, sensor, atomic force microscope, scanning tunneling microscope

Note: The basic keyword search strategy is to search for patents with any one of the designated keywords in an application area. Patents may be assigned multiple application areas if their abstracts contain keywords from more than one application area.