Original Article

From lab to market? Strategies and issues in the commercialization of nanotechnology in China

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Abstract Nanotechnology is expected by many to be one of the next drivers of technology-based business and economic growth. China has emerged as a global player in nanotechnology development, and now ranks second (after the United States) in nanotechnology scientific publications produced annually. The study of nanotechnology offers a lens to examine China's capabilities to move closer to the frontier of technology-led economic development, explore the evolving Chinese innovation system, and assess the effectiveness of policy strategies to modernize and add-value to research and industry in China. Supported by new policy initiatives and funding, hundreds of institutions and thousands of researchers in China are engaged in nanotechnology R&D. Yet, although Chinese nanotechnology research has scale, the pathways from laboratory research to successful commercialization remain problematic. Chinese performance in nanotechnology patenting and product development is weak relative to its research strength, suggesting a significant gap between the research base and industrial development. Drawing on bibliometric research and field interviews with Chinese nanotechnology policymakers, researchers and business representatives, we analyze this gap, explore the factors contributing to it and assess future commercialization trajectories.

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Introduction

Nanotechnology, which involves manipulating molecular-sized materials to create new products and process with novel features due to nanoscale properties, is widely foreseen as one of the next drivers of technology-based business and economic growth around the world (Lux, 2007; NSET, 2007). China has emerged among the leading research performers in this new technological paradigm and now ranks second (after the United States) in nanotechnology scientific publications produced annually (Zhou and Leysdorff, 2006; Tang and Shapira, 2008; Youtie *et al*, 2008). Supported by state policy initiatives and funding (Michelson, 2007; Appelbaum and Parker, 2008), over 50 universities, 20 institutes of the Academy of Sciences, several hundred enterprises and thousands of researchers in China are engaged in nanotechnology research and development.

China is still in a follower group, which includes Japan and South Korea, behind the United States and leading European countries, in aggregate measures of research quality such as the citations per paper, the proportion of publications in high impact journals or the ratio of highly cited papers compared with all papers. For example, the nanotechnology articles published in 2004 by Chinese first authors garnered an average of 2.7 citations per paper by mid-2006, compared with 5.6 and 4.3 citations per paper respectively for the nanotechnology articles published by US and German first authors (analysis of data reported in Youtie *et al*, 2008). However, the citation performance of China's nanotechnology research has increased noticeably in recent years. The nanotechnology articles published in 2000 by Chinese first authors acquired, by mid-2006, just two-fifths of the mean citations per article achieved by US first authors, whereas by the same date, the nanotechnology articles published in 2004 by Chinese first authors had gained nearly one-half of the mean citations received by their US counterparts (Youtie *et al*, 2008). There is a growing cadre of Chinese scientists undertaking world-class nanotechnology research: five of the world's 20 most-cited nanotechnology researchers are based in China (Kostoff *et al*, 2006) and China has risen to a leading position in selected nanotechnology research sub-areas (Kostoff *et al*, 2007; Appelbaum and Parker, 2008).

Yet, while Chinese nanotechnology research has scale and increasing quality, the pathways from laboratory research to successful commercialization remain problematic. Chinese performance in international nanotechnology patenting is weak relative to its research strength (Kostoff *et al*, 2006). The level of domestic nanotechnology patenting in China is much higher, but we will show that a disproportionate share of Chinese nanotechnology patents are held by universities and other research institutions rather than by industry. Hence, while there are Chinese-developed nanotechnology products in the marketplace, as yet China's activities in nanotechnology product and business development have yet to achieve the prominence seen in research production. There are Chinese companies (given the expense and enforcement problems associated with patenting in China) that are developing nanotechnology products as trade secrets and selling them into the domestic market. Yet, this may limit the ability of such companies to grow, raise capital and export. Regulatory and risk concerns may also be raised if the nanotechnology composition of a product is not openly identified. Overall, we suggest that there is a gap at present between the nanotechnology research base and the commercialization of nanotechnology knowledge in China as indicated by product and industry development. In part, this may be owing to structural weaknesses in the Chinese innovation system (including capabilities for advanced industrial research, intellectual property protection and financing for innovation). There may also be roadblocks in the communication and transfer of China's extensive nanotechnology research knowledge to industry reflecting weaknesses in university–industry research collaboration, incentives for both researchers and entrepreneurs, and the availability of technical and business consulting services in advanced technological areas.

In this article, we probe the interfaces between nanotechnology research and its commercialization in China. The study of nanotechnology offers an important lens to assess China's capabilities to move closer to the frontier of technology-led economic development and to assess the workings of the emergent Chinese innovation system and the effectiveness of policy strategies to modernize and add-value to research and industry in China. Drawing on bibliometric research and on field interviews in summer 2007 with Chinese nanotechnology policymakers, researchers and business representatives (and a follow-up visit by one of the authors to China in winter 2009), we analyze the nanotechnology research-commercialization gap and explore the institutional and other factors contributing to it. Our article begins by examining the development of nanotechnology at the national level in China and identifying patterns of activity in nanotechnology research publications, patenting and product development. We then report findings from our fieldwork. The fieldwork focuses particularly on the challenges facing new nanotechnology venture start-ups in China. Building on our field observations, we find that the public research institutions (including universities) are the major players in developing nanotechnology. Some enterprises are catching up and are active in acquiring and commercializing technology developed in public research labs. However, most of the nanotechnology enterprises that we observed focused on short-term improvements to existing products without ongoing connections to research institutions rather than using the country's available knowledge base to pursue more advanced applications over the longer term. The concluding section considers implications of our findings for nanotechnology development and policy in China.

China: An 'Early Comer' to Nanotechnology

Although there has been much recent attention to the growth of nanotechnology publications in China, the country is not a latecomer to the field – indeed, research activity in nanotechnology dates back to the 1980s. Moreover, while explicit policies to promote nanotechnology are indeed newer, China has not lagged other developed countries in national initiatives to foster nanotechnology research. For example, in 2000, the National Steering Committee for Nanoscience and Nanotechnology (NSCNN) was established to oversee and coordinate nanotechnology policies and programs in China, the same year as the comparable organizing structure in the United States – the National Nanotechnology Initiative (Shapira and Wang, 2007).

The formation of the NSCNN was preceded by a decade of prior Chinese national research investments and projects in nanotechnology. The Ministry of Science and Technology (MOST) launched a 10-year 'Climbing Project on Nanomaterial Science' in 1990 and a national basic research project for nanomaterials and nanostructures in 1999. The National High Technology R&D Program (863 Program) included nanomaterial applications as a priority field and funded a thousand nanotechnology projects with US$27 million between 1990 and 2002. The National Natural Science Foundation of China (NSFC) also sponsored a thousand project grants in nanotechnology related fields in the 1990s.

The NSCNN marked a further elaboration of state efforts to foster nanotechnology in China. Established to oversee and coordinate nanotechnology policies and programs, NSCNN's membership includes MOST, the Chinese Academy of Sciences (CAS), NSFC, the National Development and Reform Commission (NDRC), the Ministry of Education (MOE) and the Chinese Academy of Engineering. NSCNN is chaired by the Minister of MOST (Figure 1). In July 2001, MOST, NDRC, MOE, CAS and NSFC jointly promulgated the National Development Plan for Nanoscience and Nanotechnology (2001–2010) that prioritized selected nanotechnology fields and the setting up of nanotechnology R&D centers and industrialization bases. China's government spending on nanotechnology research was estimated at $220 million in 2006, second only to the United States when adjusted for purchasing-power parity (Lux, 2007).

The fostering of research and industrialization centers is a cornerstone of China's nanotechnology development strategy. In 2000, MOST founded the first national nanotechnology center – the Nanotechnology Industrialization

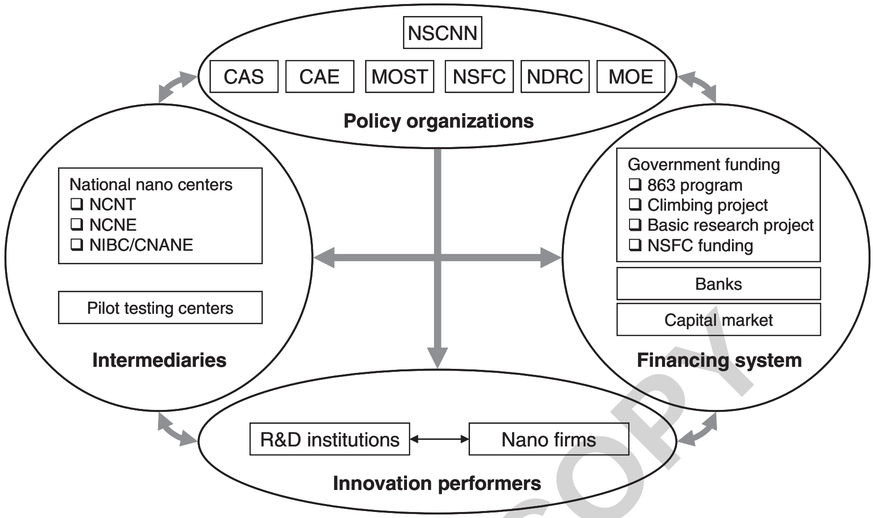

Figure 1: Nanotechnology innovation system in China.

Base of China (NIBC) in the Tianjin Economic Development Area. Shanghai's Municipal Science and Technology Commission set up the Shanghai Nanotechnology Promotion Center (SNPC) in 2001 to plan R&D projects and promote nanotechnology industrialization in Shanghai. In 2003, NDRC approved two additional centers. The National Center for Nanoscience and Technology (NCNT) in Beijing was jointly established by CAS, Peking University and Tsinghua University. The National Center for Nano-Engineering (NCNE) in Shanghai was founded by 10 organizations including three universities, three research institutes, three companies and SNPC. Another national center in Tianjin – the China National Academy of Nanotechnology and Engineering (CNANE) – was set up by CAS, Peking University and Tsinghua University in 2005 to undertake applied nanotechnology research and engineering.

Patterns of Nanotechnology Development in China

The endorsement of nanotechnology as a national priority and the availability of funding programs, nanotechnology center development, institutional support and the expansion of nanotechnology research staff (including through training young researchers and attracting overseas Chinese researchers back to the mainland) has had a propulsive effect on China's nanotechnology research output. In 2003, China overtook Japan in nanotechnology publication, becoming the second-largest nanotechnology publication producer after the United States (Figure 2). The gap between the United States and China is closing gradually over time.[1]

In interpreting the remarkable growth of Chinese nanotechnology publications, it should be noted that in recent years there has been strong encouragement (including financial incentives) for Chinese researchers to publish in international journals, especially those indexed by SCI.[2] Doctoral students are also often expected to publish at least three journal articles (SCI journals preferred) as a condition of receiving their degree. Taking these points together, it is plausible that *part* of the observed recent growth of Chinese nanotechnology publications in SCI journals reflects a shift in publication strategy from non-SCI Chinese-language to SCI mostly English-language journals.[3] Nonetheless, even allowing for this, it is undisputable that Chinese nanotechnology research output has increased dramatically (with caveats about quality, as noted in the introduction).

Unsurprisingly, universities and research institutes dominate nanotechnology publications (1990 to mid-2006), with only 3 per cent of publications listing

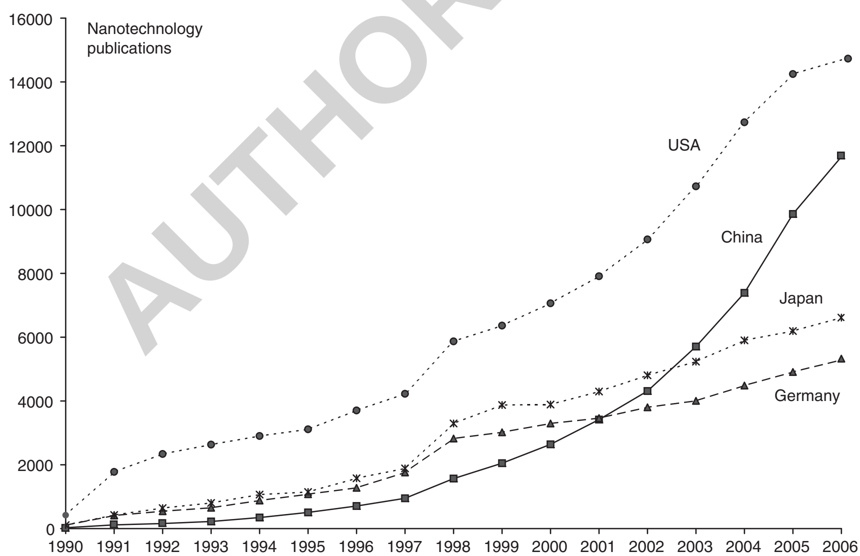

Figure 2: Leading countries in nanotechnology Science Citation Index (SCI) publications, 1990–2006.
Source: Georgia Tech global databases of nanotechnology publications, 1990–2006 (Porter *et al*, 2008). See also Note 1. Estimates for 2006 extrapolated from partial data for that year through to August.

an industry author or co-author. Five leading institutions produced over half of China's nanotechnology publications: CAS, followed by Tsinghua University, the University of Science and Technology of China, Nanjing University and Peking University (Table 1). CAS comprises more than 100 institutes and other affiliated organizations. About 20 CAS institutes are particularly active in nanotechnology research. The University of Science and Technology of China is associated with CAS, but is counted separately.

However, China's performance in international nanotechnology patents is much weaker. We compare the nanotechnology patent grants from the European Patent Office (EPO) for China and the United States (Figure 3). The EPO is selected as the destination of international patent applications instead of the USPTO to remove the home country advantage of the United States and provide a better comparison of international patenting activities between these two countries. Indeed, about 50 per cent of EPO nanotechnology patents over the period 1990–2005 were granted to European assignees (where there is a 'home' advantage), including 19 per cent to Germany, the leading European country. However, whereas 35 per cent of EPO nanotechnology patents were granted to US assignees in 1990–2005, only 1 per cent went to Chinese assignees. By comparison, assignees from Japan (which is now behind China in research publication output) were granted 11 per cent of EPO nanotechnology patents between 1990 and 2005, indicating a far greater orientation (by this measure) to the international commercialization of nanotechnology in Japan than in China.

Table 1: Top-10 Chinese institutions producing SCI nanotechnology publications 1990–2006 (mid)

Rank	*Institution*	*Number of SCI publications*	*Share (%)*
1	Chinese Academy of Science	12 829	29.3
2	Tsinghua University	2791	6.4
3	University of Science & Technology of China	2388	5.5
4	Nanjing University	2314	5.3
5	Peking University	1937	4.4
6	Jilin University	1738	4.0
7	Zhejiang University	1522	3.5
8	Fudan University	1505	3.4
9	Shanghai Jiao Tong University	1098	2.5
10	Shandong University	1056	2.4

Notes: See also Note 1. Data is for period from 1990 through to mid-2006 (August). SCI = Science Citation Index, Web of Science. Total Chinese SCI publications 1990–2006 (mid) = 43 785.
Source: Georgia Tech global databases of nanotechnology publications, 1990–2006 (Porter *et al*, 2008).

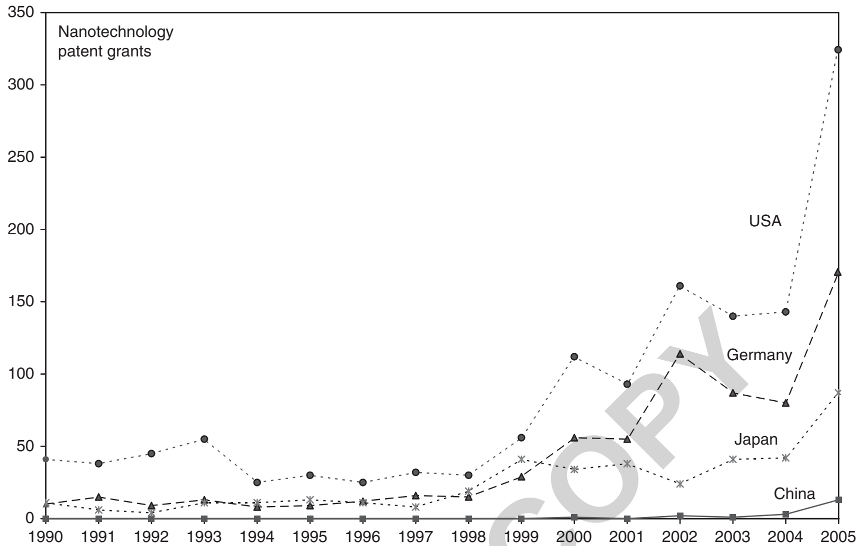

Figure 3: EPO nanotechnology patent grants by inventor country (selected), 1990–2005.
Source: Georgia Tech global databases of nanotechnology patents, 1990–2005 (Porter *et al*, 2008).
EPO = European Patent Office.

International patent applications are, of course, usually more expensive and complicated than applying for domestic patents. Typically, international patents will be sought only for particularly high-value inventions. Hence, to obtain a fuller picture of Chinese nanotechnology intellectual property development, we analyze domestic patents, as awarded by the Chinese national patent office – the State Intellectual Property Organization (SIPO). Between 1990 and mid-2006, SIPO awarded more than 4700 nanotechnology patents, mostly assigned to organizations and corporations. We acknowledge that the intellectual property regime in China has traditionally been weaker than in developed economies. However, since establishing its first patent law in 1984, China has been strengthening its procedures to recognize and protect intellectual property, especially since joining the World Trade Organization after 2002, although issues of enforcement still remain (Wang and Tang, 2008).

These system aspects notwithstanding, our examination of Chinese domestic patents suggests that what particularly differentiates China is the *profile* of patent assignees in nanotechnology. In other developed countries, industry is the main performer in industrial applications and leads in patenting. In China, university and research institutes produced most of the domestic nanotechnology patents. In the period 1990–2006, university and research institutes accounted for 58.6 per cent of patent grants in SIPO, while industry only

Table 2: Top-10 Chinese institutions awarded SIPO nanotechnology patents 1990–2006 (mid)

Rank	*Institution*	*Number of SIPO patents*	*Share (%)*
1	Chinese Academy of Sciences	974	20.6
2	Tsinghua University	206	4.3
3	Shanghai Jiao Tong University	200	4.2
4	Fudan University	159	3.4
5	Zhejiang University	149	3.1
6	Wuhan University	115	2.4
7	East China University of Science and Technology	93	2.0
8	Nanjing University	72	1.5
9	Jilin University	69	1.5
10	Tianjin University	67	1.4

Notes: See also Note 1. Data is for period from 1990 through to mid-2006 (August). SIPO = State Intellectual Property Office, China. Total SIPO nanotechnology patents identified = 4736. Total assignees identified = 1051. Rank compared with all assignees.
Source: Georgia Tech global databases of nanotechnology patents, 1990–2006 (Porter *et al*, 2008).

accounted for 18.7 per cent (compared with 51 per cent in the United States) (See note 1). The rest were granted to individuals.

Among the more than 1000 patent assignees identified in our analysis of SIPO nanotechnology patents, the top-five assignees are CAS, Tsinghua University, Shanghai Jiaotong University, Fudan University and Zhejiang University (Table 2). Indeed, 80 of the top-100 SIPO nanotechnology assignees are universities or research institutions. The leading corporate entity is Hongfujin Precision Industry Corporation, which ranks fourteenth among all Chinese SIPO nanotechnology assignees, followed by the China Petroleum Corporation (ranked twenty-sixth) and then eight companies ranked in the third and fourth quintiles (Table 3). The difference in scale of patenting by *leading* organizations by sector is remarkable: whereas the top-10 research and academic organizations account for 44.4 per cent of all SIPO nanotechnology patents, the top-10 corporations account for just 3.5 per cent of these patents. Additionally, there is a strong presence of Chinese-based subsidiaries or joint ventures of foreign companies (there are two Taiwanese and two Korean affiliates among the top-10 SIPO corporate nanotechnology patent assignees). Some leading corporate patent assignees are also linked with research or foreign organizations. For example, CAS is one of the shareholders of the third-ranked Chinese corporate nanotechnology patent awardee (Zhongke Nano Tech Engineering), while Hongfujin Precision is a subsidiary of Foxconn of Taiwan, which has a joint research center (Tsinghua-Foxconn Nanotechnology Research Center) directly on the campus of Tsinghua University.

Table 3: Leading corporations awarded SIPO nanotechnology patents 1990–2006 (mid)

Rank	*Company*	*Number of SIPO patents*	*Share (%)*
14	Hongfujin Precision Industry Co. Ltd[a]	54	1.1
26	China Petrochemical Corporation[b]	31	0.7
43	Zhongke Nano Tech Engineering Co.[c]	14	0.3
45	Chengdu Simo Nano Technology Co.[d]	12	0.3
48	Dongyuan Nano Applied Material (Teco)[e]	11	0.2
54	Sinopec Corporation[f]	9	0.2
58	Beijing Jisheng Jiye Hi-tech Co.[g]	9	0.2
59	China Lucky Film Corporation[h]	8	0.2
60	LG Electronic Tianjin Co.[i]	8	0.2
61	Samsung Co. Ltd[j]	8	0.2

[a]Subsidiary of Foxconn (Taiwan).
[b]State-owned company.
[c]Joint venture, CAS is one of the stakeholders.
[d]Joint venture.
[e]TECO (Taiwan) is the parent company.
[f]State-owned company.
[g]Private company.
[h]State-owned company.
[i]Affiliate of LG Electronics (South Korea).
[j]Affiliate of Samsung (Korea).
Notes: See also Note 1. Data is for period from 1990 through to mid-2006 (August). SIPO = State Intellectual Property Office, China. Total SIPO nanotechnology patents identified = 4736. Total assignees identified = 1051. Rank compared with all assignees.
Source: Georgia Tech global databases of nanotechnology patents, 1990–2006 (Porter *et al*, 2008).

A comparison with the United States highlights the distinctiveness of the Chinese pattern of nanotechnology development. From 1990 through to mid-2006, US universities and research organizations contributed over 90 000 nanotechnology publications and over 1000 nanotechnology patents, whereas industry produced about 11 000 nanotechnology publications and some 5000 nanotechnology patents (Figure 4). In the United States, academia dominates basic research while industry is the major player in innovation through patenting. In China, over the same time period, academic and research organizations produced 44 000 nanotechnology publications and 3000 nanotechnology (SIPO) patents while industry produced about 1000 nanotechnology publications and also about 1000 nanotechnology patents. Chinese universities and public research institutions are taking leading roles in both basic research and innovation patenting, whereas Chinese firms are relatively much weaker both in research publication and, most importantly, in innovation patenting. In addition, co-authored publications and co-patents

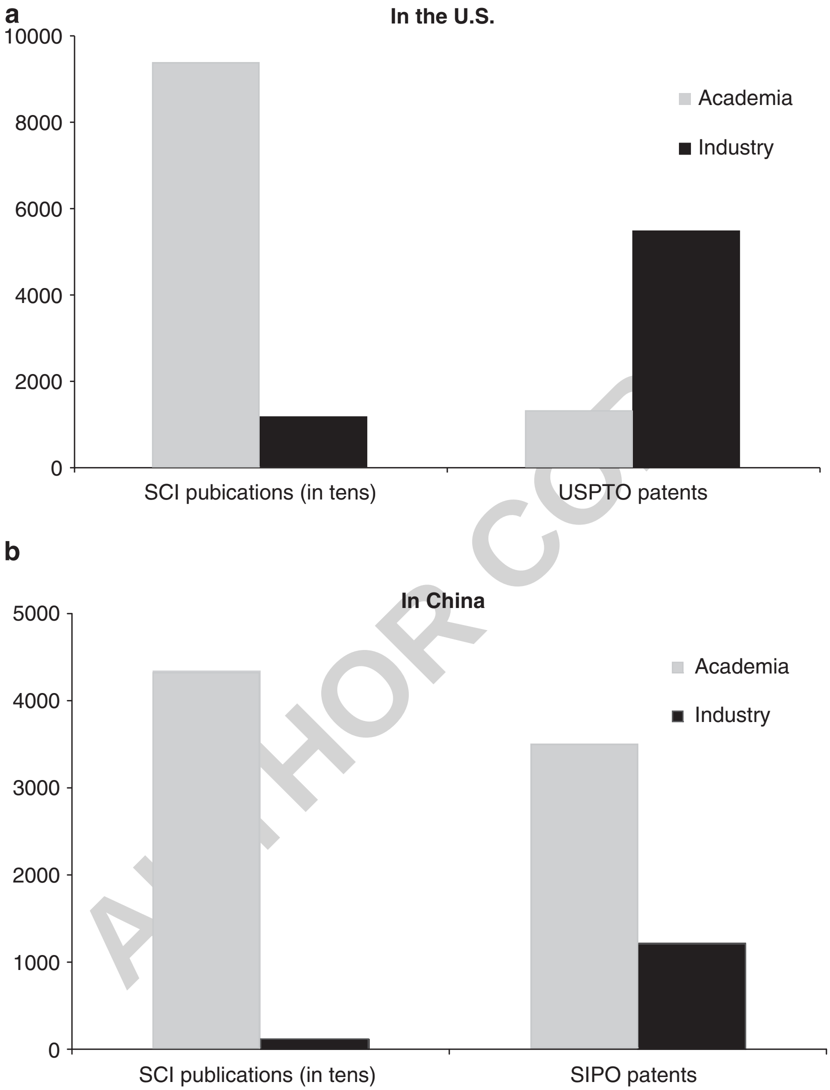

Figure 4: Nanotechnology R&D indicated by publications and patents, 1990–2006 (mid).
Source: Georgia Tech global databases of nanotechnology publications and patents, 1990–2006 (Porter *et al*, 2008). See also Note 1. Data are for period from 1990 through to mid-2006 (August). SCI = Science Citation Index, Web of Science; USPTO = United States Patent and Trademark Office; SIPO = State Intellectual Property Office, China.

between academia and industry in the United States are 6000 and 65, respectively, while in China, the numbers are 1000 and two. Formal academic–industry collaboration is much lower in China as reflected in these two indicators.

In understanding the profile and structure of nanotechnology patenting in China, particularly when compared with the United States and other countries where industrial organizations are typically leaders in patenting, three factors are relevant. First, for researchers at CAS and in universities, the production of patents (as well as publications) is incentivized and can be an important element in career development and promotion.[4] Second, with the opening up of China to private business development and the relaxation of university consulting and outside business rules, university researchers are among those who seek to start their own technology businesses. University-related science parks and similar schemes have been founded in China to encourage this. Similarly, Chinese research institutions and universities themselves establish or take ownership positions in technology-oriented businesses, and in other cases research centers run business operations to secure additional income for their scientific activities. For example, CAS has converted several of its research institutes into companies, directly lists 20 companies under its oversight (including Legend Holdings, which itself owns Lenovo – the company that acquired IBM's personal computer operations in 2005), and has invested in or created more than 400 science and technology-based business ventures (CAS, 2003a; Blanpied, 2007). Under its 1998–2010 'Knowledge Innovation Program', CAS seeks to 'become China's major incubator for the development of high-tech industries' (CAS, 2003b; Suttmeier *et al*, 2006).[5]

Third, the industrial sector in China has historically lacked research and innovation capability. China's innovation system followed the Soviet model in the 1950s, with a division of labor among universities, research institutes and industry. Universities were mainly responsible for education, research institutes performed R&D and industry was only engaged in development and production (Xue, 1997). In this system, industry was largely isolated from R&D activities while R&D performers had little incentive to commercialize their research results. The structural reform of the Chinese innovation system, started in 1985, sought to improve communication between R&D and industrial applications, and strengthen industrial innovation capabilities. Industry participation in science and technology has since increased, particularly for China's burgeoning high-technology sector. Nevertheless, most industrial technological activities are focused on applied development or implementing R&D results in production. Where industry undertakes applied research, usually this is undertaken by large- and medium-sized enterprises. As in other countries, Chinese small firms are usually less able to invest in R&D because of the lack of financial resources and staff capabilities.

Moreover, in recent years, the rapid growth of domestic and export demand in China has not encouraged long-term corporate R&D, as companies have found that they can sell all they can make without taking the risks and costs of new product or process development. Weak IP protection has also served as a disincentive for Chinese companies to engage in R&D, although the Chinese government is now strengthening IP enforcement. Chinese technology companies, particularly small or midsize, but also including larger firms, have generally preferred to collaborate with researchers in research organizations and universities and to license or set up joint ventures with these organizations. Some foreign companies, particularly from Taiwan, Korea and elsewhere in Asia, are also using this strategy, developing close links with top university researchers and institutions and transfersing technologies to Chinese-based affiliates or joint ventures.

However, although high-level university leaders and state policymakers in China are encouraging stronger academic-industry linkages, there are still on-the-ground obstacles. Besides the weaknesses of companies in absorbing university R&D, university departments themselves are often disciplinary-based and oriented towards research goals and publications. When universities patent, this can be driven by motivations for career development and institutional recognition rather than commercialization. Targeted initiatives such as university-related science parks do not necessarily ensure that university-industry knowledge and technology transfer links flourish.[6] In a 2004 survey of high-tech enterprises in ZhongGuanCun in Beijing (the largest science park in China and located adjacent to many universities and CAS), only 26 per cent of enterprises reported some cooperation with academia, whereas 40 per cent of enterprises in the science park indicated zero or very little interaction with R&D institutions (Wang and Zhao, 2005). More than a third of respondents reported that they lacked financial resources and R&D capabilities to absorb technology developed in academia. This is the framework for R&D and commercialization in China.

We suggest that these specific characteristics of the Chinese national innovation system are influential in setting the pathways for nanotechnology development and commercialization within the country. The key flagstones of this path comprise a mixture of top-down and bottom-up responses, including state prioritization and the expansion of national resources for nanotechnology research; the substantial expansion of research activities and publication outputs in nanotechnology by Chinese research organizations and academic institutions; the development of IP in nanotechnology in the domestic arena by those research organizations and academic institutions; and efforts to transfer knowledge (through patent licensing, business incubation, joint ventures and other informal and less linear forms of transfer) to companies for business and product development. At the same time, although noticeably weaker, there is some corporate R&D activity in nanotechnology in China, including by foreign-affiliated companies.

In the next section of this article, we further explore China's pathway of nanotechnology development from laboratory to market, from an industrial perspective. With the importance of research-stimulated business incubation and researcher-to-business technology transfer to the Chinese pathway of nanotechnology development, we focus particularly on cases of the development of small- and mid-size nanotechnology firms, on the relationships they have established, and the challenges encountered.

Nanotechnology Company Development and Relationships in China

Estimates of the number of companies in China active in nanotechnology range from over 300 (Bai, 2005) to more than 800 (Hariharan, 2005). Many of China's nanotechnology enterprises work with nanoparticles and carbon nanotubes particularly in the chemical and materials manufacturing industries. Generally, these nanotechnology outputs are incorporated into other consumer and industrial products. Examples of 37 Chinese-made nanotechnology products on the market include nano-waterproof neck ties, nano-silver (antibacterial) food storage boxes and nanofiltration membranes to filter water (Project on Emerging Technologies, 2006). Industrial applications include the manufacture of ceramic nanoparticles for paints, the production of carbon nanotubes for high-strength composites and conductive materials, and field-emission displays (Lux, 2004).[7] Overall, much of China's nanotechnology industry is in nanomaterials and manufacturing, which is at the lower end of the nanotechnology value chain (Lux, 2007). China lacks higher-end business activity in nanoelectronics and bio-nanotechnology/medical applications, which require long-term capital and R&D investments as well as advanced scientific capabilities.

To probe the development of nanotechnology enterprises and the drivers of their research and production activities, we held 24 in-depth interviews with nano-scientists in universities and research institutes, nano-firm representatives, government officials and policy scientists. Our visit covered three cities Beijing, Shanghai and Tianjin, which are the main nanotechnology bases and locations of national nanotechnology centers in China. These three cities jointly contributed half of the nanotechnology publications (47 per cent) and patents (53 per cent) in China. Interviews with five small nanotechnology enterprises are summarized below (see also Table 4). These firms were identified from entries found in the commercial International Nanotechnology Business Directory (website: www.nanovip.com). The five case studies were selected to be illustrative of different varieties of start-ups, including enterprises spun-out from research institutes or universities, joint ventures between smaller

Table 4: Summary information on nanotechnology venture cases

Firm and city	*A (Beijing)*	*B (Shanghai)*	*C (Shanghai)*	*D (Shanghai)*	*E (Shanghai)*
Year founded	2006	2006	2002	2003	1998
Product	Fuel additive	Metal powder and solutions	Nano-PCC	Nanofiber	Polymer; nanopowder
Background	Founded by graduate student, currently a post-doc	Transformed from another company	Established by a state-owned enterprises jointly with other firms	Founded based on a technology licensed from a CAS institute; the founder has other family based business	Founded by a university professor
Type	Private	Private	Joint venture	Private	Private
Funding source	Self-invest	Self-invest	Self-invest (investment from the shareholder); one government project	Self-invest; only one government project	Self-invest; government funding (SNPC and SME Innovation Funding)
Employment (R&D)	10 (3 R&D)	100 (5 R&D)	200 (150 in factories; 20 R&D)	18 (0 R&D)	80 (20 R&D)
R&D	Limited R&D; product testing and improvement	Own R&D center; product development	Own R&D center; doing product application and process improvement	Little R&D	Own R&D center; doing product design, technical service, application development
Patents	1	Many	10	2	30

Table 4 *continued*

Firm and city	*A (Beijing)*	*B (Shanghai)*	*C (Shanghai)*	*D (Shanghai)*	*E (Shanghai)*
Sales	Very little (amount not disclosed)	RMB 30 million	RMB 10 million	RMB 6 million	RMB 50 million
Exports	No	10% of sales	20% of production	30% of sales	Not disclosed
Advantages	Technology	—	Equipment; R&D center	—	Technical service; costs low compared with MNCs
Obstacles	IPR disputes; Short of money	High cost of products	—	Funding; R&D capability	Market
Links with public nanocenter	No	No	Yes, close; but not helpful	Yes, broad links; but do not see benefits	Yes, for connection with other companies
Links with universities	Using facilities in the university lab	Consulting researchers from Korean or university scientists when necessary	Working with universities to solve problems and test applications	Having a joint lab with CAS institute but the lab only being used once or twice a year; no collaboration with universities	Using university equipments when needed

Source: Field research by authors in China, interviews conducted with companies, June–July, 2007.

and larger firms, and enterprises with no initial connections with either research institutes or larger firms.

Firm A. Nanotechnology fuel additives

Firm A is a nano-start-up company in Beijing, close to Tsinghua and Peking Universities and CAS research institutes. The firm produces a fuel additive using 'nano self-constructed technology', which is claimed to improve fuel consumption in vehicles and reduce harmful emissions. The company was founded in 2006 and grew to about 10 employees by 2007, with 2–3 R&D personnel and 4–5 marketing/sales personnel. It has a small factory to manufacture its own products. The technology was invented in 1999 by a college student, who then founded Firm A to market this technology. Only minor improvements have since been undertaken. Firm A does assess the performance effects of the additive on different fuels, but this work is mostly done in university labs, as the companies' few R&D workers are affiliated with universities.

Money is a major issue for the company. The firm is self-financed. According to the firm manager, government resources, such as the High-tech SME Innovation Fund or Nanotechnology Industrialization Centers, are not easily accessible to small firms like Firm A. Also, very few venture capitalists are willing to invest in nanotechnology products because of uncertainty and risk. Marketing is another issue. Nanotechnology is not in itself a selling point to customers for several reasons including customers' difficulty in understanding what nanotechnology is. So, the company demonstrates test results to convince customers of the advantages of its product.

Assessment: This company offers a simple nanotechnology-enabled product to individual retailers and consumers, but lacks scale, marketing power and product-appeal. The company is not directly linked with universities, although is able to draw on university resources through informal connections due to the founder's affiliation with the university. It does not have an active R&D program or easy access to funding to develop additional products.

Firm B. Nanoscale cleaning technology

Firm B is regarded as among the leading nanotechnology firms in China in terms of the scope and scale of nanotechnology research and production. The founder set up an air cleaning company after returning from abroad, including work in nanotechnology. In 2006, he transformed that firm into the current Firm B and relocated to Shanghai. Firm B now focuses on air cleaning technologies using nanoscale materials (for filtration) and offers 180 product versions in 10 industrial fields. There are 100 employees, half of whom are factory production workers. Firm B has its own R&D center with five researchers, and works closely with the foreign company where the founder spent 8 years. Firm B also maintains good relationships with local universities and occasionally invites university scientists to participate in research projects that Firm B cannot accomplish by itself.

With revenues of 30 million yuan (US$3.9 million) in 2007, Firm B has positive cash flow and invests in research with its own funding. Its management reports that they have not had significant government funding partly because they perceive government funding as limited but also because the application process is viewed as time-consuming. Research facilities are available onsite except for product testing. Management comments that the lack of skilled R&D personnel is a problem for the sustainable development of Firm B. In addition, Firm B is also having a difficulty in advertising and marketing its nanotechnology concepts, as most of its customers do not understand nanotechnology or why it provides benefits.

Assessment: Company B is successfully exploiting a particular nanotechnology product niche, drawing on technology originally acquired by the founder while abroad and incrementally developed in conjunction with that foreign firm and with local university researchers. In this sense, the company is a 'spin-in' rather than a 'spin-out'. Government programs are not accessible, but this does not seem much to matter. What is important to the company is attracting new R&D personnel.

Firm C. Ultrafine precipitated calcium carbonates

Shanghai-based Firm C is one of the country's largest companies producing ultrafine precipitated calcium carbonates (PCC). Ultrafine PCCs are used in many building materials, including sealants and in polyvinyl chloride (PVC) products (such as vinyl window frames) where ultrafine or nanoscale PCCs are used to improve product rigidity and to reduce the amount of PCC material needed for a given level of strength. Firm C is a joint venture, with a Shanghai-based state-owned construction material company as the largest stakeholder. It was founded in 2002 with registered capital of $12 million. The current annual sales are around 10 million yuan ($1.4 million). Firm C has two factories, one of which hosts an in-house R&D center, and employs 200 individuals including 20 R&D personnel and 150 factory workers. Firm C does two types of R&D: application development and process improvement. Firm C combines advanced testing equipment including transmission electron microscopy with the well-established Brunauer–Emmett–Teller method for estimating surface areas (Brunauer *et al*, 1938). Before Firm C purchased its own facilities, it used university laboratories. Firm C still collaborates with university laboratories to conduct tests of PVC profiles and applications. Firm C is affiliated with SNPC and uses the center to access new information.

Firm C's advantages in the Chinese market are viewed by management as its R&D capabilities and its self-developed technologies (as most Chinese competitors have neither). In addition, as the state-owned construction material company is a stakeholder and recommends or even requires some construction companies to use products from Firm C, Firm C has good marketing channels. However, the high cost of production due to capital investment costs for equipment is a major concern for Firm C in expanding its market. Firm managers also observe that in the first period of enthusiasm for nanotechnology in China in the early 2000s, many Chinese firms used the label 'nano' as a tag to make their products appear sophisticated and to seek premium pricing (even when there was no actual nanotechnology content). The resulting distrust among consumers means that products cannot be sold anymore just by promoting them as nanotechnology. Instead, Firm C advertises its technology as an ultrafine product with characteristics that can be better controlled through its manufacturing processes.

Assessment: Ultrafine PCCs have been used for a long period of time. Nanotechnology tools and methods allow the properties of ultrafine PCCs to be better understood, measured, controlled and manufactured. Firm C is thus an example of incremental innovation, using nanotechnology tools to improve an existing product, and doing it successfully in the Chinese market (aided by a powerful stakeholder and customer). Current links with universities are modest, mainly for testing, and nanotechnology center use is primarily for exchange and information gathering. There are numerous manufacturers of ultrafine PCCs in the Chinese market, so expansion to new customers (particularly outside of construction) is subject to fierce competition. This firm may find it difficult to move out of its current, highly competitive, market niche without significant new knowledge and research investments.

Firm D. Antibacterial materials and fibers

Firm D is a Shanghai manufacturer of antibacterial and antimicrobial inorganic powders and fibers using, in particular, silver nanoparticles. Permeating or coating materials with silver nanoparticles greatly enhances the well-established antibacterial properties of silver (because of the large surface area of nanoparticles compared with their volume). Firm D is a spin-off from a company working on traditional minerals after the founder decided to explore new applications. The company has 18 employees. It was established in 2003 based on technologies licensed from a CAS institute. The director of the institute, who is the inventor of the technology, serves as a science advisor for Firm D. Firm D has a research project with the CAS institute and has set up a joint lab, which is used once or twice a year. For the rest of the time, the lab is not in use except for doing some testing by technicians from the factory. Firm D's focus is on technology application and marketing. R&D carried out in Firm D is mainly pilot testing. Firm D has close relationship with SNPC in order to use its testing service as it has more authority. It also has connections with universities to access their lab facilities but has little contacts with other firms. Firm D belongs to the Shanghai Nanotechnology Association (SNA) and seeks to link with other R&D institutions via SNA.

Firm D reported its advantage resides in its scale of production and sales. Its development strategy is also to expand production and sales. However, since Firm D is a family-based business, the availability of funding is a major issue for its continuous development. It started with 3 million yuan ($0.4 million) investment and currently has 6 million yuan ($0.8 million) annual sales. At 90 thousand yuan ($11.8 k) per ton, nanofibers are three times more expensive than regular fibers, which makes it difficult for Firm D to increase its market and generate more revenue. Technology is another challenge for Firm D, as the firm does not have sufficient R&D capability to apply its technologies in different areas. Firm D plans to recruit more R&D personnel to do more application research but has no plan yet for an R&D center.

Assessment: Firm D is a spin-out from a CAS research institute, which was the source of its original technology. However, many Chinese companies manufacture silver nanoparticles for antibacterial applications, so this is a competitive commodity market. To be distinctive in the market, Firm D needs to develop new applications. Yet, potential demand is uncertain and expansion financing is hard to secure. Moreover, although Firm D seems well connected with research institutes, universities and a national nanotechnology center, its own lack of R&D capability makes it difficult to exploit these links.

Firm E. Polymers and nanopowders

Firm E was founded in 1998 by a professor, who then resigned from the university in 1999 to work full time in Firm E. It is a private company and is wholly owned after buying back the share held by a government venture capital firm in 2000. Firm E started with the manufacture of polymers and surface products and changed its product line to focus on nanotechnology-enabled products in 2002. Its main products are polymers, nanopowders, nanocatalysts, flooring materials and coatings. Principal customers are in the ceramics, paper industry and environmental treatment industries.

Firm E employs 80 persons and has an R&D center with 20 R&D personnel. The R&D center works on product design, technical service and application development. Firm E mainly does product applications because it does not have enough R&D capability to be engaged in major new product development. Firm E works with the founder's former university to use university equipment because its own equipment is limited. Firm E has no other collaboration with R&D institutions or companies. Although SNPC has facilities, Firm E prefers to use those in the university because these are less expensive. Firm E's annual revenues are about 50 million yuan ($6.6 million).

Firm E believes that its advantage over other companies lies in its ability to provide technical services. These are used to customize products and applications. There are few domestic competitors in the same markets as Firm E, while compared with international competitors Firm E has price advantages. The shortage of funding is not an issue for Firm E at this stage. However, Firm E noted the general difficulty of obtaining external funding including government funding or VC investment. As reported by other firms, marketing is a challenge for Firm E because nanotechnology is not necessarily well-understood, and is sometimes distrusted, by potential customers.

Assessment: R&D functions of Company E focus on customization of applications rather than new product development, and the company is competing (in a commodity marketplace) on the basis of better service than other Chinese companies and lower cost than international suppliers. Despite being founded by a former university professor, it does not have capabilities for new product R&D, and although it uses university testing facilities, it does not work with universities on new product development.

Insights from the Field Research

The Chinese nanotechnology enterprises that we studied were all manufacturing products in the field of nanomaterials, such as nanopowders and nanofibers, which is consistent with previous studies such as the Lux Report (2007). Their products are used mainly in coatings, formulas, additives, plastics and construction materials. Most of them are young and small- to medium-sized firms, ranging from 1 to 9 years old and from 10 to 200 employees. The background of their founders is not homogeneous, varying from start-ups by professors or graduate students to company spin-offs and transformed firms.

However, the firms do exhibit similarities in strategies and face common challenges, as discussed below.

These firms are largely reliant on an initial core technology, which was either developed by the founder or licensed from universities or research institutes. If they undertook further R&D, this was focused on the incremental modification of the core technology and applying it in different areas, with little emphasis on developing new technologies. Surprisingly, they rarely undertook substantive research collaborations with universities. The most frequent forms of academic interactions were using facilities in university labs and consulting university scientists with technical questions.

Technological deficiency is a problem mentioned most often by companies during the interviews, in addition to the lack of funding and market. Owing to the complex nature of nanotechnology, companies often find it difficult to develop technology applications in different fields. For example, Firm D reported that a customer would like to apply Firm D's technologies for dental applications, which not only requires that the material has strong performance but also brings challenges in terms of production cleanliness and product safety. Firm D had to give up on this because its R&D team was not able to accomplish this task. In another case, Firm E stated that their R&D activities were restricted to product applications because they did not have enough R&D capability for major new technological developments.

Hence, an interesting paradox emerges. On the one hand, China has greatly expanded its academic research staff and research publication outputs in nanotechnology, but firms in the industry indicate that the lack of internal R&D capability is one of the major bottlenecks that restrain the growth of nanotechnology enterprises in China, particularly in moving up the nanotechnology value-chain. There appears to be an institutional divide, where R&D personnel in nanotechnology are not only more attracted to universities and other research institutions than to companies, but once employed in a research institution, the institutional incentives do not sustain a strong technology transfer component. Many firms are aware of this problem, but they have not begun to actively seek solutions. Their connection with universities and research institutes is limited. These firms are not updated with research conducted in universities and are little able to benefit from it. Companies see academic research as too basic and far from industrial applications, whereas universities – while active in patenting – are not as motivated as might be hoped to transfer knowledge for industrial applications. To date, the national nanotechnology centers that we visited do not appear to be significantly crossing or addressing this divide.

At the same time, in interviews with university scientists, several expressed an interest in developing commercial applications of their research and creating spin-offs, although the extent of interest varies from one to another. Some realize their research is too early for market at this moment and would like to wait until they get further findings, whereas others stated their commercialization activities are already on the way. In a few cases, we found nano-scientists who were actively engaged with industry. In one interview, a university scientist reported that over 30 per cent of research funding in his group came from industry, including patent licensing, contract research and joint research projects. He would like to further commercialize his research but lacks skilled people for this. Hence, he is particularly interested in collaborating with existing industry partners. The problem he has been faced with is to identify the right partner.

Based on the information collected during interviews, academic research, in spite of its limit, is a potential source for nanotechnology enterprises to get R&D input. Perhaps only a small share of current academic nanotechnology research has potential for further industrial development. But there are barriers both to the formal and informal transfer and sharing of this knowledge. Due in part to historical factors (such as the separation of research from production under Chinese state planning) and current incentives to build up international research reputations, university scientists are often not greatly aware of, or motivated by, potential industrial applications of their research, while on the other hand, nanotechnology enterprises are not informed about research developments in academia. Although there are no doubt exceptions, by and large we see that Chinese universities remain focused on the production of publications and patents as *measures* of research performance rather than as *instruments* of knowledge transfer. Meanwhile, most companies lack resources and absorptive capabilities to fully access what Chinese nano-researchers may be able to offer.

One set of companies that seems more able to cross this institutional divide is foreign enterprises operating in China. Perhaps the best example is Foxconn – a manufacturer of electronics and computer components headquartered in Taiwan – which has set up a nanotechnology research center at Tsinghua University. This center does research with potential benefit to Foxconn but not necessary with direct application to current products, whereas Foxconn's other R&D centers do more applied research and product development. Nanotechnology scientists in Tsinghua University work in this center on research questions interesting to Foxconn or to themselves with funding coming solely from Foxconn. They meet with representatives from Foxconn frequently to exchange information on market needs and research progress. By 2007, this center has made over 300 patent applications worldwide.

In addition to Foxconn, other foreign enterprises with nanotechnology interests that are visible in the Chinese market include Veeco Instruments (US) and Rohm and Haas (US), as well as foreign firms with substantial nanotechnology R&D such as IBM (US), Intel (US), GE (US) and L'Oréal

(France). These enterprises have set up various research collaborations with Chinese universities. For instance, Shanghai Jiaotong University, Shanghai University and the Institute of Applied Physics at CAS have started collaborations in several areas of nanotechnology including nano-optics and nano-biotechnology with Essilor (a French company) and Invitek (a German company) in 2007 (Wang, 2007).

These examples of foreign enterprises working together with Chinese universities indicate that certain parts of academic research on nanotechnology can be used by industry. On the other hand, as noted, some domestic nanotechnology enterprises may not have enough absorptive capacity to exploit knowledge generated by universities and research institutes. As indicated in an interview with a university scientist, he is interested in collaborating with an industrial partner who has at least some technology background. Companies with limited R&D capabilities are less favored in university–industry collaboration. For these companies, it is easier for them to learn from other industry peers, especially foreign companies, whose knowledge is more applied and tangible.

Given the existence of foreign nanotechnology enterprises in China, and more to come in the foreseeable future, knowledge spillovers to local enterprises are likely, and this would seem to be an additional pathway from the lab to the market for Chinese nanotechnology. Local firms can gain access to advanced technologies of their foreign counterparts reverse engineering, labor mobility, demonstration effects and vertical spillovers in supplier–customer relationship (Blomstrom and Kokko, 1998) or in the more direct form of technology licenses or subcontracts (Baranson, 1970). Compared with technologies developed in academia, which are often too distant to industrial users, technologies developed by foreign enterprises operating in a host country may be more readily absorbed by domestic enterprises. This proposition is also consistent with knowledge spillover theories of multinational companies that suggest that host countries benefit from foreign direct investment (FDI) through enhanced access to advanced technologies as well as through employment creation and cash flow (Teece, 1977; Aitken and Harrison, 1999). Indeed, studies have already provided evidence for the positive impact of FDI on the innovation capabilities and R&D activities of domestic enterprises in China (Hu and Jefferson, 2002; Cheung and Lin, 2004).

Conclusions

The development of nanotechnology research in China has been greatly aided by government initiatives through a top-down approach. Recognizing the opportunities brought by nanotechnology, the Chinese government started to invest on nanotechnology in early 1980s. A cabinet-level organization – NSCNN – has been set up to coordinate national nanotechnology policies and activities. Nanotechnology is listed as one of the priorities in major national research programs and projects. Several national nanotechnology centers with various emphases are founded to promote the development of nanotechnology. The government expenditure on nanotechnology is comparable with other industrialized countries. By making early moves and making substantial efforts, China is expecting to compete with other countries and take a leading position in this new field. The amount of the nanotechnology publications suggests the success of the country in this aspect. China is among the top-three countries in producing nanotechnology publications since 2000.

However, looking beyond publication data reveals a different story. The rank of China is rather low when using the measurement of international nanotechnology patents; while the analysis of domestic nanotechnology patents suggests an unbalanced relationship, with universities and research organizations much more engaged in nanotechnology patenting than corporations. There are Chinese-made nanotechnology products on the market, but mostly these are at the low, commodity-end of the nanotechnology product value chain. Our field visits to companies could not be comprehensive, but the selective interviews that we did conduct indicated that small- and medium-sized Chinese nanotechnology enterprises frequently were established based on a few core technologies either self-developed or licensed from R&D institutions. In general, these enterprises lacked sustained R&D capabilities. Most of them were set up to make profits from their core technologies and have no long-term research agenda. Their R&D workforce is largely focused on minor product improvement or technology applications and is not able to conduct major technology development. These enterprises do not have much cooperation with universities or research institutes beyond using equipment or seeking modest technical advice. Interaction with other companies also seems rare.

In summary, in probing how China's upgraded and up-scaled R&D capabilities in nanotechnology can support commercialization, two pathways have been identified: spillover from academia and spillover from foreign enterprises. The pathway from academic R&D to commercial applications in China, at least as far as small technology-driven firms are concerned, is strewn with obstacles. Chinese policymakers have expanded nanotechnology R&D, but the translation of research into technology or products is largely missing in the government's agenda. While policy goals are broad and do include economic impact, the effective result of the program implementation methods and incentives employed is a focus more on encouraging the producing of knowledge but less on making use of produced knowledge. This may reflect the dominance of scientists and representatives of CAS and universities in the highest levels of Chinese science and technology policymaking. Few programs are targeting R&D activities within nanotechnology enterprises. Commercial banks and venture capital (which is only just starting to emerge in China) are as yet not greatly interested in this domain. So, new nanotechnology firms in China mostly have to rely on self-investment and self-development, although there are insightful cases of joint-venture development with larger industrial corporations. While the research stage of nanotechnology in China can be described as a top-town model as the government is the initiator, the industrialization process is more like a bottom-up approach that has yet to gain momentum.

Nonetheless, there are some outward signs of change. The Chinese government has recently set up several national nanotechnology centers to promote not just R&D but also the commercialization of nanotechnology, such as NIBC, CNANE, NCNT and NCNE. While NCNT aims at advancing basic research in nanotechnology, all the other centers have the goal to facilitate applied research and commercialization of nanotechnology. In addition to applied research, these centers have initiated other exchange and relationship-building activities. For example, national and international nanotechnology conferences have been held in several locations in China. Joint project funding has been made available to link university scientists together with companies. Nanotechnology associations have been organized to allow enterprises work together. Nevertheless, these centers are still in their early development stage and have not yet achieved their ultimate goals.

Bridging foreign enterprises and domestic enterprises appears to be another practical way to improve R&D capabilities of these nanotechnology enterprises. While the importance of university–industry cooperation has been recognized and emphasized, little attention has been devoted to the collaboration between domestic enterprises and foreign enterprises. It is unclear whether local nanotechnology alliances involve foreign nanotechnology enterprises and encourage their interaction with domestic enterprises. Given the fact that some Chinese universities already have research collaboration relationships with foreign enterprises, it might also be helpful to domestic enterprises if they can become more fully engaged in these collaborations.

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Notes

1 This article draws on global databases of nanotechnology publications and patents developed at Georgia Institute of Technology using the definition of nanotechnology and methods described in Porter *et al* (2008). The data sets cover the period 1990–2006 (mid) and include more than 400 000 nanotechnology publication records in the Web of Science's Science Citation Index (SCI) and nearly 54 000 abstracts of nanotechnology patents awarded in this time frame obtained from the MicroPatents database. It is recognized that SCI varies in strength by subject area (SCI is excellent for most life and physical sciences, but not quite as strong in chemical, medical and engineering research.) Also, SCI does not cover all scientific journals, and in its coverage is weaker for scientific journals that publish in languages other than English. The patents database covers the United States Patent and Trademark Office (USPTO), European Patent Office (EPO), Japan Patent Office (JPO), World Intellectual Property Office, and multiple national patent offices including those of Germany, Great Britain, France and China.

2 To put this in perspective, we note that in the United States and increasingly in other advanced countries, there is also strong encouragement for researchers to publish in journals, including those indexed by SCI, and journal publication is a major factor in promotion and tenure.

3 Lin and Zhang (2007) find that *Chinese-language* SCI publications in nanotechnology have increased rapidly in recent years, supported by a growing community of mainland Chinese nanotechnology researchers (including students as well as senior researchers lacking English capabilities).
4 In some institutions, graduate students can seek patents as an alternative to publishing journal papers to secure their degrees. This pathway is not yet common among Chinese students (one reason being that papers can be published more rapidly than patents can be filed, examined and awarded).
5 Other leading universities are as ambitious as CAS in incubating businesses and in acquiring intellectual property (IP). As measured by the ratio of SIPO patents to SCI papers, Tsinghua University produces one patent for every 13.5 papers, which is similar to the ratio for CAS (one patent per 13.1 papers). Among the leading universities, Shanghai Jiao Tong University is particularly focused on IP relative to publications, receiving one patent for every 5.5 papers published.
6 This is not a problem exclusive to China. University science and technology parks around the world often are not as strong as anticipated in fostering university–company linkages (see, for example, Phan *et al*, 2005).
7 Neither of these two Chinese companies analyzed by Lux held US patents, although they did hold Chinese patents.

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