This is a paper in progress. Comments and suggestions will be greatly appreciated

From lab to market?

Strategies and issues in the commercialization of nanotechnology in China

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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 2006; NSET 2007). China has emerged among the research leaders in this new technological paradigm and now ranks second (after the US) in the total number of nanotechnology scientific publications produced annually (Youtie et al 2008; see also Zhou and Leysdorff 2006; Tang and Shapira 2008). Supported by extensive new state policy initiatives and funding (Michelson 2007; Applebaum 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 commercialization.

China is still in a follower group, which includes Japan and South Korea, behind the US and other leading European countries, in standard measures of overall research quality such as the proportion of publications in high impact journals or the ratio of highly cited papers compared with all papers. However, the quality of China's nanotechnology research has increased noticeably in recent years in terms of citations, in some sub-areas of nanotechnology research China has a leading position, and there are numerous Chinese scientists undertaking high-level nanotechnology research (Kostoff et al. 2006; Appelbaum and Parker 2008; Youtie et al 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., 2007). 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 appears to be a gap at present between the nanotechnology research base and industrial development in China. But what is the significance of this gap, what underlies it, and – most important – is it showing signs of closing?

This paper probes the interface between nanotechnology research and its commercialization in China. Drawing on bibliometric research and field interviews with Chinese nanotechnology policymakers, researchers, and business representatives, we analyze the nanotechnology research-commercialization gap and explore the policy, institutional, economic, social and cultural factors contributing to it. Our field work focuses particularly on the challenges facing new nanotechnology venture start-ups in China. We build on these field insights to examine current discussion and action about the challenges of nanotechnology commercialization in China and assess future commercialization trajectories.

While our focus in this paper on nanotechnology, we seek also to distill some broader insights. We suggest that study of nanotechnology represents an important lens through which to assess China's capabilities to move closer to the frontier of technology-led economic development, to explore the workings of the emergent Chinese innovation system (see also Wang 2007), and to assess the effectiveness of policy strategies to modernize and add-value to research and industry in China.

China: An “Early Comer” to Nanotechnology

Although there has been much recent attention to the rapid growth of nanotechnology publication activity in China, the country is not a latecomer to the field – indeed, research activity in nanotechnology dates back to the 1980s. Moreover, while organized policy activities to promote nanotechnology are indeed newer, China has not lagged other developed countries in national initiatives to foster and coordinate nanotechnology research. For example, in November 2000, the National Steering Committee for Nanoscience and Nanotechnology (NSCNN) was established to oversee and coordinate nanotechnology policies and programs in China. The comparable organizing structure in the US – the National Nanotechnology Initiative – was formed around the same time, in fiscal year 2001 (Shapira and Wang 2007).

However, just as in the case of the NNI, the formation of the NSCNN was preceded by almost a decade of prior Chinese national research investments and projects in nanotechnology. For example, MOST launched a ten-year “Climbing Project on Nanomaterial Science” in 1990 and a national basic research project of nanomaterial and nanostructure 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 $27 million in the period 1990-2002. The NSFC also provided a thousand grants for projects in nanotechnology related fields in the 1990s.

The formation of the NSCNN marked a further elaboration of state efforts to foster nanotechnology in China. Established to oversee and coordinate nanotechnology policies and programs, the principal members of NSCNN include the Ministry of Science and Technology (MOST), the Chinese Academy of Sciences (CAS), the National Natural Science Foundation of China (NSFC), the National Development and Reform Commission (NDRC), the Ministry of Education (MOE) and the Chinese Academy of Engineering (CAE). NSCNN is chaired by the Minister of the MOST (Figure 1). In July 2001, MOST, NDRC, MOE, CAS and NSFC jointly promulgated the National Development Plan for Nanoscience and Nanotechnology (2001-2010) to propose nanotechnology development strategies for the next ten years. This plan prioritized selected nanotechnology fields and the setting up of nanotechnology R&D centers and industrialization bases. Lux Research has estimated China's government spending on nanotechnology at US$ 250 million in 2005, second only to the US when adjusted for purchasing-power parity (Lux Research 2005).

[Insert Figure 1 here]

The fostering of nanotechnology research and industrialization centers is one of the cornerstones of China's nanotechnology development strategy. Indeed, prior to the endorsement of this strategy in the 2001 National Development Plan, the first national nanotechnology center was founded (in December 2000) by MOST – the Nanotech Industrialization Base of China (NIBC), located in Tianjin Economic Development Area (TEDA). The Science and Technology Commission of Shanghai Municipality set up the Shanghai Nanotechnology Promotion Center (SNPC) in July 2001 to plan R&D projects and promote nanotech industrialization in Shanghai. In 2003, NDRC approved two additional national nanotechnology centers. The National Center for Nanoscience and Technology (NCNT) in Beijing was jointly established in March by CAS, Peking University and Tsinghua University. The National Center for Nanoengineering (NCNE) in Shanghai was founded in November by ten organizations including three universities, three research institutes, three companies and SNPC. Tianjin's NIBC was subsequently complemented by another center – the China National Academy of Nanotechnology and Engineering (CNANE), set up jointly by

CAS, Peking University and Tsinghua University on the same site in May 2005, in order to promote applied research and engineering of nanotechnology.

The Pattern of Nanotechnology Development in China

The endorsement of nanotechnology as a national priority and the simultaneous 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 output, becoming the second largest nanotechnology publication producer next to the United States (Figure 2). The gap between the US and China is closing gradually over time.[1]

[Insert Figure 2 here]

In assessing the remarkable growth of Chinese nanotechnology publication, 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 Science Citation Index (SCI).[2] Doctoral students are also often expected to publish at least three journal publications (again, with a preference for SCI-listed journals) as

[1] The bibliometric analyses in this paper draw on the 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. (2007). The datasets cover the period 1990-2006 (mid) and include more than 400,000 nanotechnology publication records in the Web of Science's Science Citation Index and nearly 54,000 abstracts of nanotechnology patents awarded in this timeframe 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 USPTO, EPO, JPO, World Intellectual Property Office (WIPO), 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 US 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.

a condition of receiving their degree. Taking these points together, it is plausible that *part* of the observed recent growth of Chinese nanotechnology publication in SCI journals reflects a shift in publication strategy from non-SCI Chinese-language to SCI mostly English-language journals.[3] Additionally, as noted in the introduction, aggregate measures of Chinese nanotechnology research quality suggest that China is still in the follower-pack among leading nanotechnology research nations.

Yet, these caveats made, it is undisputable that Chinese nanotechnology research output has increased dramatically. It is also evident that the quality of Chinese nanotechnology research is improving, with performance in some sub-sectors and by selected researchers and elite institutions moving towards the international frontier of the field (Kostoff et al. 2006). Over the period 1990-2006 (mid), five leading institutions jointly accounted for over half of China's nanotechnology publications: CAS[4], followed by Tsinghua University, the University of Science and Technology of China, Nanjing University and Peking University (Table 1). Unsurprisingly, universities and research institutes dominate research activities in this field. In China, 99.6% of nanotechnology publications were contributed by researchers from universities and research institutes in 1990-2006 while only 3% were from industry (some were co-authored by researchers from both sectors).

[Insert Table 1 here]

However, China's performance in nanotechnology industrial applications as indicated by international patents shows a different picture in terms of the scale of activity. Figure 3 presents the number of nanotechnology patent grants from the European Patent Office (EPO)

[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] CAS comprises more than 100 institutes and other affiliated organizations. Our analysis indicates that about 20 CAS institutes are most active in nanotechnology research. The University of Science and Technology of China is also associated with CAS, but is counted separately.

for China and the US. The EPO is selected as the destination of international patent applications instead of the United States Patent and Trademark Office (USPTO) to remove the home country advantage of the US and provide a better comparison of international patenting activities between these two countries. While 35% of EPO nanotechnology patents were granted to US assignees in 1990-2005, only 1% went to Chinese assignees.

[Insert Figure 3 here]

Patent applications outside of one's home country are, of course, usually more expensive and more 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, it is also necessary to look at domestic Chinese patents, as awarded by the Chinese national patent office – the State Intellectual Property Organization (SIPO). For the period 1990-2006 (mid), our analysis of the Georgia Tech global nanotechnology dataset (using the definition of nanotechnology described in Porter et al. 2007) indicates that SIPO awarded more than 4,700 nanotechnology patents, mostly assigned to organizations and corporations.

What differentiates China most from other countries is the *profile* of patent assignees. Unlike other developed countries, where industry is the main performer in industrial applications of nanotechnology, university and research institutes again produced most of the nanotechnology patents filed in SIPO in China. In the period 1990-2006, university and research institutes accounted for 58.6% of patent grants in SIPO, while industry only accounted for 18.7% (compared with 51% in the US). The rest were granted to individuals.

Among the more than 1,000 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 14th among all Chinese SIPO nanotechnology assignees, followed by the China Petroleum Corporation (ranked 26th) 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 ten research and academic organizations account for 44.4% of all SIPO nanotechnology patents, the top ten corporations account for just 3.5 % 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 ten SIPO corporate nanotechnology patent assignees). Moreover, linkages are also observable between research and corporate 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 built a joint research center (Tsinghua-Foxconn Nanotechnology Research Center) directly on the campus of Tsinghua University.

[Insert Table 2 and Table 3 here]

A comparison with the US highlights the distinctiveness of the Chinese pattern of nanotechnology development. As shown in Figure 4, from 1990 through to mid-2006, US universities and research organizations contributed over 90,000 nanotechnology publications and over 1,000 nanotechnology patents, while industry produced about 11,000 nanotechnology publications and some 5,000 nanotechnology patents. In the US model, academia dominates basic research while industry is the major player in innovation through patenting. By contrast, in China, over the same time period, academic and research organizations produced 44,000 nanotechnology publications and 3,000 nanotechnology

(SIPO) patents while industry produced about 1,000 nanotechnology publications and also about 1,000 nanotechnology patents. This signals a picture where universities and public research institutions are taking leading roles in both basic research and innovation patenting, while Chinese firms are relatively much weaker both in research publication and, most importantly, in innovation patenting. In addition, co-authored publications and co-patents between academia and industry in the US are 6,000 and 65 respectively, while in China, the numbers are 1,000 and two. Research collaboration activities are much lower in China as reflected in these two indicators.

[Insert Figure 4 here]

In understanding the profile and structure of nanotechnology patenting in China, particularly when compared with the US 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.[5]

Second, with the opening up of China to capitalism and private business development, an increasing proportion of scientists and university faculty seek to explore opportunities to start their own technology businesses. Many 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 businesses 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

[5] In some institutions, graduate students can seek patents as an alternative to publishing journal papers to secure their degrees. However, our understanding is that this pathway is not yet very common among Chinese students (one reason being that papers can be published more rapidly than patents can be filed, examined, and awarded).

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 "become China's major incubator for the development of high-tech industries" (CAS 2003b; Suttmeier et al. 2006).[6]

Third, most Chinese companies lack capabilities to undertake research and invention. In part, (as discussed in the next section), this is a carryover from the period of state enterprise management where the industrial sector was charged with production, with research undertaken elsewhere. 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 clear division of labor among universities, research institutes and industry. Universities were mainly responsible for education, research institutes had a sole function of R&D, and industry was only engaged in development and production (Xue 1997). In this system, the industry sector 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, was designed to improve the communication between R&D and industrial application, and strengthen industrial innovation capabilities. Since then, the industry sector has started to participate in more science and technology activities, and this is particularly true for the burgeoning Chinese 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 (LMEs). As in other countries, Chinese small firms are usually less able to invest in R&D due to the lack of financial resources and staff capabilities.

[6] Other leading universities are as ambitious as CAS in incubating businesses and in acquiring intellectual property. 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 intellectual property relative to publications, receiving one patent for every 5.5 papers published).

Moreover, in recent years, the rapid growth of domestic and export demand in China has not necessarily encouraged long-term corporate R&D, since many companies have found that they can sell all they can make without taking the risks and costs of new product or process development. The lack of a strong intellectual property (IP) regime has also served as a disincentive for Chinese companies to engage in R&D, although the Chinese government is now strengthening IP protection and enforcement. Chinese technology companies, particularly if 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 transferring technologies to Chinese-based affiliates or joint ventures.

However, forming effective relationships between companies and university and other research institutions is often not easy. Top-level university leaders and state research policymakers in China are encouraging stronger university-industry linkages, but 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. This includes an emphasis on publication, but even when universities patent at least in part in can be as a result of staff motivations for career development and institutional motivations for recognition rather than commercialization. Even targeted initiatives such as university-related science parks do not necessarily ensure that university-industry knowledge and technology transfer links flourish.[7] According to a survey conducted in 2004 on high-tech enterprises in ZhongGuanCun in Beijing, which is the largest science park in China and

[7] 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.

located adjacent to many universities and CAS, only 26% of enterprises reported some cooperation with academia, while 40% of enterprises in the science park indicated zero or very little interaction with R&D institutions (Wang and Zhao 2005). In responding to a question about barriers in university-industry collaboration, 21.7% of the enterprises reported that academic research was not applicable in the market and 33.9% reported that they did not have enough financial resources and R&D capabilities to absorb technology developed in academia. In the nanotechnology domain, several of the national centers (such as NIBC in Tianjin and SNPC in Shanghai) as well as local university centers have explicit goals to foster commercialization. Whether these centers are effective in assisting nanotechnology companies is a topic that we will further discuss in the next section.

This overview suggests that the development of the nanotechnology enterprise in China (by which we mean the activities both of R&D and commercialization in nanotechnology) is taking a path which is specific to the structure and characteristics of the Chinese national innovation system. The key flagstones of this path comprise a mixture of top-down and bottoms-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 intellectual property in nanotechnology in the domestic arena by those research organizations and academic institutions; and the transfer of both formal and tacit knowledge (through patent licensing, business incubation, joint ventures, and other 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, and some products on the market. But to bolster their capabilities, Chinese companies active in nanotechnology are likely to seek relationships with research institutions, universities, and nanotechnology development centers to develop their nanotechnology products and business lines.

In the next section of the paper, 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

There are no authoritative statistics on the number of companies active in the nanotechnology industry in China. Estimates range from over 300 (Bai 2005) to 800 (Hariharan 2005) or more. However, it does appear that many of China's nanotechnology enterprises are working primarily with nanoparticles and carbon nanotubes particularly in the chemical and materials manufacturing industries. Generally, these nanotechnology outputs are incorporated into other products, including ones targeted to consumers as well as other industrial uses. 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 Research 2004).[8] Overall, assessed against schematic interpretations of the nanotechnology value chain (Figure 5), China's nanotechnology industry's main business is

[8] Neither of these two Chinese companies analyzed by Lux held US patents, although they did hold Chinese patents.

nano materials and manufacturing and is still in the low end of the value chain. Mostly, China lacks higher-end nano business activity in nano-electronics and bio-nanotechnology/medical applications which require long-term capital and R&D investments as well as scientific capabilities.

[Insert Figure 5 here]

To probe the development of nanotechnology enterprises and the drivers of the research and production activities, a field study was conducted in summer 2007. We had twenty-four 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%) and patents (53%) in China. Table 1 summaries the attributes of nanotechnology enterprises we visited. The description of each firm is presented as follows.

Firm A. Nanotechnology fuel additives

Firm A is a nano start-up company, located in the Haidian District of Beijing, close to Tsinghua and Peking Universities and CAS research institutes. The main product of Firm A is fuel additive, which is claimed not only improving fuel consumption in vehicles but also reducing harmful emissions with the use of the “nano self-constructed technology.” 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 in his junior year. The inventor founded Firm A to market this technology. Only minor improvements have since been undertaken. R&D work in Firm A is primarily the assessment of the performance effects of the additive on different fuels. Mostly this work is done in university labs since the companies' few R&D workers are affiliated with universities.

The firm is self-financed and money is the main issue for the company. According to the firm manager, government resources, such as the High-tech SME Innovation Fund or Nanotech 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 its high uncertainty and risk. Marketing is another issue. Nanotechnology is not attractive to customers for several reasons (including customers' difficulty in understanding what nanotechnology is). Therefore, the sales personnel of Firm A cannot use nanotech as a marketing point. Instead, they have to demonstrate test results to convince customers of the advantage of the product.

Bottom-line: This company is seeking to sell a simple nanotechnology-enabled product to individual retailers and consumers, but lacks scale and marketing power and potentially product-appeal to make major inroads. The company is not directly linked with universities, although through informal connections is able to draw on university resources. It does not have an active program nor 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 he returned from abroad, where he spent eight years and was involved in nanotechnology related work. 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 ten industrial fields. There are 100 employees, half of whom are factory production workers. Firm B has its own R&D center with 5 researchers, and works closely with the foreign company where the founder spent eight years. Firm B also maintains good relationship with local universities and occasionally invites university scientists to participate in research projects that Firm B cannot accomplish by itself.

With revenues of RMB 30 million in 2007, Firm B has positive cash flow and is able to invest in research with its own funding. Government funding is rare since it is hard for Firm B to apply for project funding from government programs. 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 advertizing and marketing its nanotechnology concepts since most of its customers do not understand nanotechnology or why it provides benefits.

Bottom-line: 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

Firm C is one of the largest companies that produce ultra fine precipitated calcium carbonates (PCC) in China. 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. It is a joint venture, with a Shanghai-based state-owned construction material company as the largest stake holder. It was founded in 2002 with registered capital of $12 million. Currently Firm C has 2 factories, one of which hosts an in-house R&D center. There are 200 employees working in Firm C including 20 R&D personnel and 150 factory workers. Firm C does two types of R&D: application development and process improvement. Firm C is equipped with advanced testing equipment and methods including transmission electron microscopy (TEM) and BET (a method for estimating surface areas). Before Firm C purchased its own facilities, it went to universities to use their laboratories. Firm C collaborates with universities for application testing, such as extruding, PVC, and PVC profile testing. Firm C also is affiliated with the Shanghai Nanotechnology Promotion Center and uses the center to access new information.

Management view own-technology and R&D capabilities as Firm C's advantages in the Chinese market (since most other Chinese competitors have neither). In addition, since the state-owned construction material company is a stake holder and recommends or even requires some construction companies to use products from Firm C, Firm C has a good marketing opportunity. However, the high cost of production due to capital investment costs for equipment is a major concern for Firm C in expanding its market. Also, since the nano concept is not attractive to customers, Firm C cannot use it as a selling point and instead advertises the technology as ultrafine products.

Bottom-line: 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 other manufacturers of ultrafine PCCs in the Chinese market so expansion to new customers (particularly outside of construction) is subject to fierce competition.

Firm D. Antibacterial Materials and Fibers

Firm D manufactures 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 (due to 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 some 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 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 since it has more authority. It also has certain connections with universities to have access to their lab facilities but has little contacts with other firms. Firm D is a member of Shanghai Nanotechnology Association (SNA) with the hope to have connections to other R&D institutions via SNA.

By owning a factory, 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 investment and currently has 6 million Yuan annual sales. Due to the high price of nanotechnology products, e.g. 90 thousand Yuan per ton for nano fiber vs. 30 thousand Yuan per ton for regular fiber, Firm D has a hard time to increase 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.

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

Firm E. Polymers and nano powders

Firm E was founded in 1998 by a university professor, who then resigned from the university and has been working full time in Firm E since 1999. 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, nano powders, nano catalysts, 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 since it does not have enough R&D capability to be engaged in major product development. Firm E works with the founder's former university in order to use university facilities since it has limited equipments on site. But except for that, Firm E has no collaboration with R&D institutions or other companies. While SNPC has facilities, Firm E prefers to use those in the university since it is much less expensive there. The annual revenue of Firm E is around 50 million Yuan.

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 not many 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 that it is rather difficult to get external funding including government funding or VC investment. Firm E suggested that maintaining good relationship with government such as providing public service to the government and the public or participating activities organized by the government is critical in getting government projects.

Marketing is a challenge for Firm E since the nanotechnology concept is not accepted or understood by customers. Firm E has to demonstrate its performance and quality in order to convince its customers.

Bottom line: Company E was started by a former university professor, and then subsequently moved into nanotechnology applications. Its R&D functions 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. It does not have the 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 nano-materials, such as nano-powders and nano-fibers. 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. However, the background of their founders is not homogenous, varying from start-ups by professors or graduate students to company spin-offs and transformed firms.

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 are through 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. Due to the interdisciplinary and complex nature of nanotechnology, companies often find it difficult to develop technology applications in different fields. For example, Firm A reported that a customer would like to apply Firm A'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 A had to give up on this because its R&D team was not able to accomplish this task. In another case, Firm B 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 started to actively seeking solutions. Their connection with universities and research institutes is very limited. These firms are not updated with research conducted in universities and are not able to be benefited from it. Companies see academic research as too basic and far from industrial applications, while 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 (and the firms that we studied who were connected with these centers) 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, while 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% 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 enough manpower for that. Hence, he is particular 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 university scientists are not aware of potential industrial applications of their research, while on the other hand, nanotechnology enterprises are not informed about research developments in academia. Yet, there are also structural problems. By and large, Chinese universities remain very focused on the production of publications (and patents) as measures of performance of research; 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 are 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, while 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 and Rohm and Haas, as well as foreign firms with substantial nanotechnology R&D such as IBM, Intel, GE, and L'Oréal. 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 few examples of foreign enterprises working together with Chinese universities indicate that certain parts of academic research on nanotechnology can be utilized 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 collaborate 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 concept also fits with the knowledge spillover theory of multinational companies, which suggests the access to advanced technology in addition to the employment creation and complementary cash flow as the benefits of foreign direct investment (FDI) bringing to the host economy (Teece 1977; Aitken and Harrison 1999). Several studies provided evidence for the positive impact of FDI on the innovation capability 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.[9] 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. Even if there

[9] As yet, our research has not focused on larger Chinese companies involved in nanotechnology.

is some, the cooperation is no more than using equipment or seeking modest technical advice. The interaction with other companies is even 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. Few policies or programs are targeting R&D activities in nanotechnology enterprises. Venture capitalists 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 since the government is the initiator, the industrialization process is more like a bottom-up approach which has yet to gain momentum.

The Chinese government has realized the importance of developing applications of nanotechnology and set up several national nanotechnology centers to promote the R&D and 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. Some efforts are on the way. 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 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 relationship 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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Figure 1. Nanotechnology innovation system in China

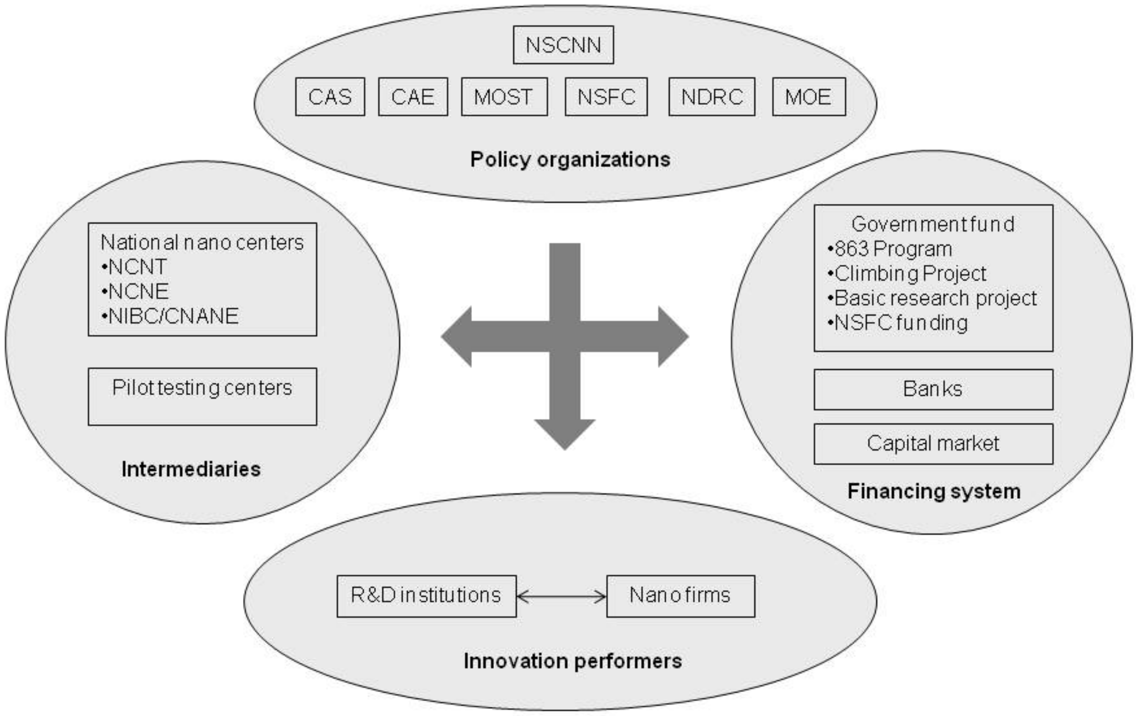
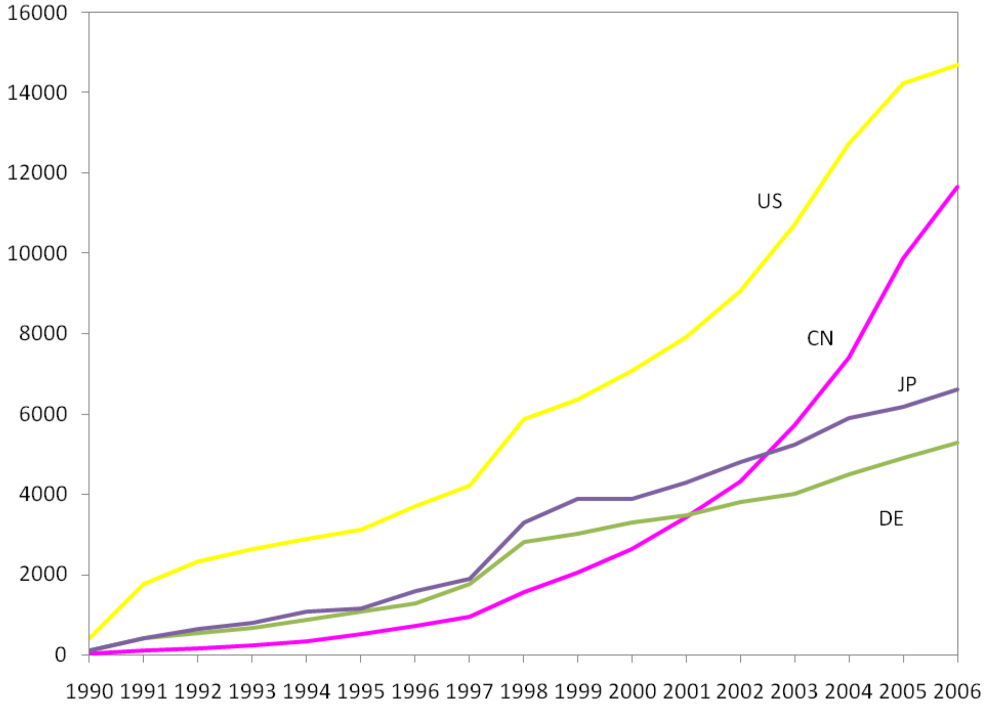
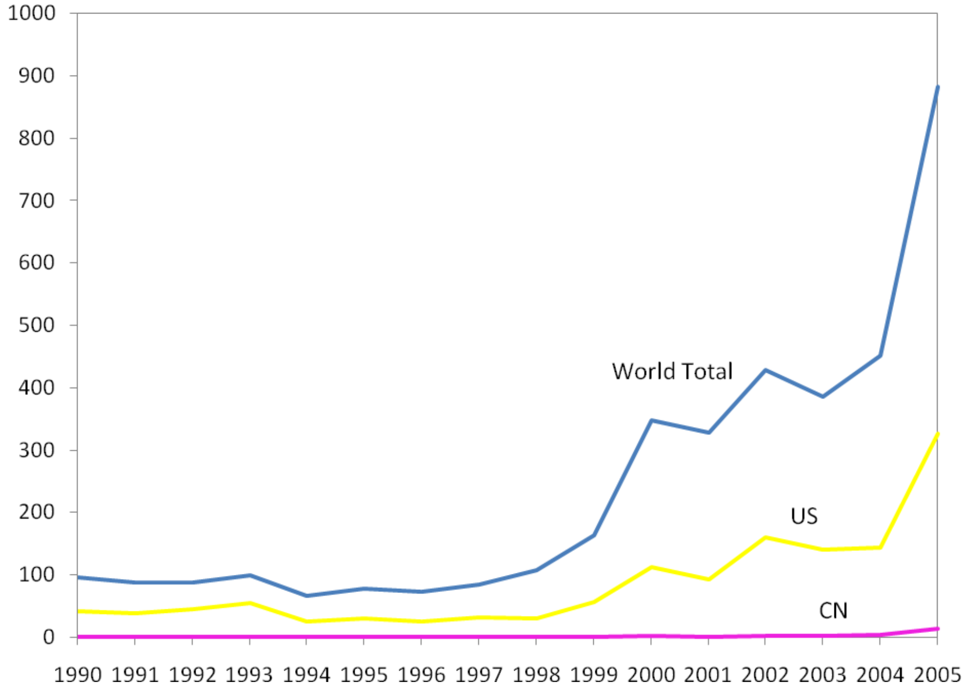


Figure 2. Leading countries in nanotechnology SCI publications, 1990-2006*



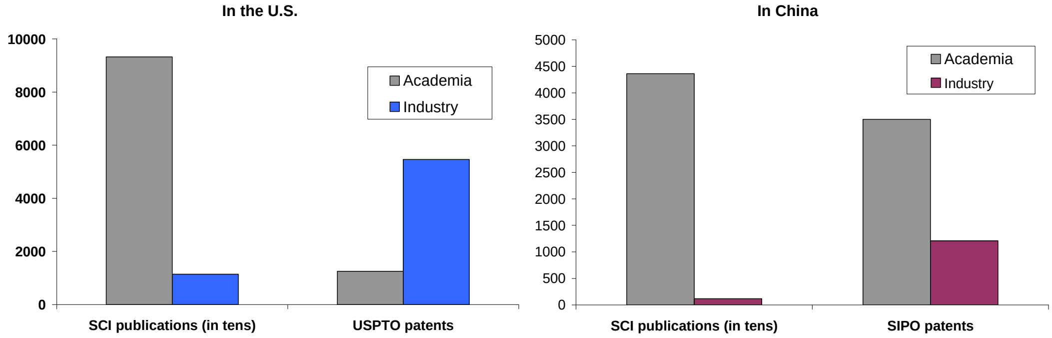
Source: Global nanotechnology publication dataset developed by the CNS-ASU Georgia Tech team using refined nanotechnology search terms (Porter, Youtie, Shapira, & Schoeneck, 2007); computed by the authors. *mid.

Figure 3. EPO nanotechnology patent grants by inventor country, 1990-2005



Source: Global nanotechnology patent dataset developed by the CNS-ASU Georgia Tech team using refined nanotechnology search terms (Porter et al., 2007); computed by the authors

Figure 4. Nanotechnology R&D indicated by publications and patents



Source: Global nanotechnology publication and patent datasets developed by the CNS-ASU Georgia Tech team using refined nanotechnology search terms (Porter, et al. 2007); computed by the authors

Figure 5. Nanotechnology value chain

	Nanomaterials	Nanointermediates	Nano-enabled products
Manufacturing and materials	Nano particles Nanotubes Quantum dots Fullerenes	Coatings Fabrics	Apparel Processed food Plastic container Construction materials Appliances
Electronics and IT		Memory Chips Contrast media Optical components	Computers Consumer electronics
Healthcare and life sciences		Drug discovery and delivery Nanosensors Nanotherepeutics	Pharmaceuticals Medical devices

Source: (Lux Research 2006; Porter, Youtie et al. 2007)

Table 1. Top 10 Chinese institutions producing SCI nanotechnology publications 1990-2006*

Rank	Institution	Number of SCI Publications	Share
1	Chinese Academy of Science	12829	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%

Source: Dataset developed by the CNS-ASU Georgia Tech team using refined nanotechnology search terms (Porter et al., 2007); computed by the authors. Total Chinese SCI publications between 1990-2006 (mid) = 43,785. *mid.

Table 2. Top 10 Chinese institutions awarded SIPO nanotechnology patents 1990-2006*

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%

Source: Global nanotechnology patent dataset developed by the CNS-ASU Georgia Tech team using refined nanotechnology search terms (Porter et al., 2007); computed by the authors. Total SIPO nanotechnology patents identified = 4,736. Total assignees identified = 1,051. Rank compared with all assignees. *mid.

Table 3. Leading corporations awarded SIPO nanotechnology patents 1990-2006*

Rank	Company	Number of 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%

Source: Global nanotechnology patent dataset developed by the CNS-ASU Georgia Tech team using refined nanotechnology search terms (Porter et al., 2007); computed by the authors. Total SIPO nanotechnology patents identified = 4,736. Total assignees identified = 1,051. Rank compared with all assignees. *mid.

Notes: a. Subsidiary of Foxconn (Taiwan); b. State-owned company; c. Joint venture, CAS is one of the stake-holders; 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).

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	Nano fiber	Polymer; nano powder
Background	Founded by a graduate from Peking University; currently a post-doc in Tsinghua University	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 professor from Eastern China University of Science and Technology.
Type	Private	Private	Joint venture	Private	Private
Funding source	Self-invest	Self-invest	Self-invest (investment from the share-holder); 1 government project	Self-invest; only 1 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	Very little R&D	Own R&D center; doing product design, technical service, application development
Patents	1	many	10	2	30
Sales	N/A	RMB 30 million	N/A	RMB 6 million	RMB 50 million
Exports	No	10% of sales	20% of production	30% of sales	N/A
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

Firm and City	A (Beijing)	B (Shanghai)	C (Shanghai)	D (Shanghai)	E (Shanghai)
Links with public nano center	No	No	Yes, very closely; but not helpful	Yes; don't see benefit now but expect to have broad connection	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 during period June 19 – July 4, 2007.