Early Patterns of Commercial Activity in Graphene

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Abstract

Graphene, a novel nanomaterial consisting of a single layer of carbon atoms, has attracted significant attention due to its distinctive properties, including great strength, electrical and thermal conductivity, lightness, and potential benefits for diverse applications. The commercialization of scientific discoveries such as graphene is inherently uncertain, with the lag time between the scientific development of a new technology and its adoption by corporate actors revealing the extent to which firms are able to absorb knowledge and engage in learning to implement applications based on the new technology. From this perspective, we test for the existence of three different corporate learning and activity patterns: 1) a linear process where patenting follows scientific discovery; 2) a double-boom phenomenon where corporate (patenting) activity is first concentrated in technological improvements and then followed by a period of technology productization; and 3) a concurrent model where scientific discovery in publications occurs in parallel with patenting. By analyzing corporate publication and patent activity across country and application lines, we find that, while graphene as a whole is experiencing concurrent scientific development and patenting growth, country and application specific trends offer some evidence of the linear and double-boom models.

Keywords:

Graphene; commercialization; publication; patent

Introduction

The adoption of science-driven technologies typically follows an uneven path. At times, adoption is rapid, but more often the pathway is bumpy and patchy, affected by factors such as limited knowledge of future product capabilities, process integration compatibilities with current manufacturing practices, and uncertainty about market acceptance. To explore some of the nuances of these commercialization patterns, this paper examines early corporate entry and activity in graphene.

Graphene is a revolutionary nanotechnology material comprised of a single layer of carbon atoms in a hexagonal lattice pattern. This gives graphene distinctive features, including great strength, electrical and thermal conductivity, and lightness. In 2010, the Nobel Prize in physics was awarded to University of Manchester researchers Andre Geim and Konstantin Novoselov for their pioneering work on graphene (Nobelprize.org, 2011). Graphene is anticipated to have great potential in a range of diverse applications such as enhancing performance in photon sensors, solar cells, display screens, composites, and building materials (Segal 2009). In electronics, graphene is referenced in the International Roadmap for Semiconductors, along with carbon nanotubes, as an emerging research material that will be important to interconnects, directed self assembly for lithography extension, and assembly and package materials (ITRS 2010). Some analysts anticipate that graphene may have a less risky environmental, health, and safety (EHS) profile than other carbon-based nanomaterials because it is nanoscale in only one-dimension (Segal 2009). These EHS claims have yet to be fully validated: if they are, graphene applications may experience additional impetus.

Although the science underlying graphene is still undergoing intensive investigation, there is already a significant and growing body of research knowledge about this new material and its characteristics. This research investigates two mechanisms – publishing and patenting – that offer initial evidence of enterprise interest in discovery and exploitation. We explore the relationships between these two mechanisms and consider what they tell us about early strategies of firm learning and commercialization. Engagement in scientific publication by firms (often in collaboration with university and public laboratory researchers) is an indication that these firms are active in seeking and acquiring new knowledge and capabilities to better understand an emerging technology. Engagement in patenting (which involves effort and expense in filing and maintaining patents as well the cost of research) suggests that firms are interested in exploiting (or potentially making it difficult for others to exploit) the knowledge and capabilities gained through research by targeting novel applications that may have competitive and commercial implications.

In the next section, we briefly review key literature and explain our methodological approach. We present descriptive findings and interpret the present state and evolution of graphene corporate publishing and patenting. These results are used to explore the patterns and strategies of early-stage graphene corporate entry and activity among countries, sectors, and leading firms. As well as examining relationships between corporate publication and patenting, we also identify various end-user application factors (i.e. logical clusters) that are then used to highlight activities of leading firms. The final part of the paper presents conclusions.

Literature Review

The adoption of new technologies by firms is rarely straightforward or uniform. New technologies typically follow diverse and, at times, fragmented adoption rates and trajectories. At the company level, the decision to adopt a new technology is often framed by the uncertainty and risk it poses to the adopting unit. Firms draw on searching scopes that encompass internal and external knowledge to explore and learn about new technologies so as to assess the relative advantages of further exploiting existing technologies, generating or acquiring new technologies, or some combination of both strategies (March 1991, Katila and Ahuja 2002, Rogers 2003). The feasibility and potential value of the exploration of new technologies versus exploitation of existing technologies depends on whether the firm has or can establish the necessary competencies to address the opportunities and risks associated with the new technology or whether such capabilities are lacking and a tendency toward inertia prevails (Kogut and Kulatilaka 2001). A firm may pursue technological product or process innovations for competitive advantage but must weigh the benefits of the innovation with the concomitant costs of developing the new technology (Abernathy and Utterback, 1976).

In game theoretic terms, this dilemma can be modeled as a “waiting game” in which uncertainty and rivalry determine the threshold at which a firm adopts a new technology (Hoppe, 2002). Here, uncertainty refers to the arrival and value of the innovation while rivalry considers the type of interaction in the product market. The dilemma facing high-technology firms consists of both the commercial potential of the technology as well as current opportunity costs and future risks associated with product failures. Depending on a firm’s internal rate of return and its value assessment of a new technology, it may choose to wait or adopt. Whereas adopting at the outset may provide first-mover advantages, waiting may offer better opportunities to capitalize on knowledge spillovers from technological improvements that originate from outside the firm. Furthermore, having greater capacity to store and process information increases the value of waiting. Waiting may not indicate idleness; rather, firms with greater absorptive capacity (or seeking to develop such capacity) may take additional time to acquire and process information in order to reduce risk and uncertainty (Cohen and Levinthal 1989). Notwithstanding, incentives to wait are moderated by expectations of the technology's profitability (Hoppe, 2000); that is, if competitor firms predict a sufficient return based on information spillovers, they will engage in preemptive adoption in order to secure a portion of market share. Lieberman and colleagues also suggest that some companies find it is more beneficial to be the first to enter a new market if they have the pre-entry resources and expertise because early entry enables control of complementary assets, pricing that incorporates premiums and rents, and early market prominence which reinforces the advantageous position. On the other hand, another set of firms find the fast follower or second to enter position to be more beneficial because of the ability to learn from initial entrants, respond more quickly to market changes, and reduce customer education costs. (Lieberman and Montgomery 1988, 1998; Helfat and Lieberman 2002.)

The nature of the appropriability regime may also influence the decision to be an early entrant or a follower. Mechanisms for appropriability are diverse but include patenting, trade secrets, and other contracting tools, as well business strategies such as learning and pursuing first mover advantages (Cohen et al., 2000). It has been suggested that firms have greater first mover incentives in technological areas in which imitation barriers can be erected by patenting (Tuppura et al., 2010). In addition, some technologies enable a positively reinforcing cycle for early entry whereas incentives to be a later mover may be higher for technologies in which complementary capabilities (such as manufacturing or marketing specializations) retain their values (Teece 1986). We posit that graphene benefits from appropriability mechanisms in most global markets, which would encourage early entry by firms engaged in graphene R&D. On the other hand, it is unclear at this juncture whether graphene will eventually supplant capabilities in certain incumbent technologies (such as silicon), thereby advancing early entry incentives, or reinforce their value, thereby supporting follower motivations.

In determining whether and how to adopt a new technology, there are a series of factors that influence firms' decision-making. These embrace firm-level capabilities to adopt the new technology, relationships with customers' technical needs, market factors including the influence of others and opportunities for positive network externalities (Liebowitz and Margolis 1995), sectoral or industrial conditions affecting the advantage from being the first mover, and factors such as the availability of finance, suppliers, and other forms of support. Porter (1990) argues that innovation is driven by industrial structure as well as input conditions, related and supporting industries, demand conditions, and government influences. Nelson and Winter (1982), Edquist (1997), and Lundvall (1992) suggest that differences in adoption of new innovations reflect particular attributes of sectoral and national innovation systems. The innovation systems perspectives stress system and evolutionary factors including the role of learning within and between firms, interactions among enterprises and institutions, and systems of knowledge development and innovation. Sectoral innovation systems are composed of diverse networks of multinational firms, customers, suppliers, and linkages with universities and government laboratories that may cross national boundaries (Malerba, 2005). Sectoral classifications suggest that some types of firms, such as science-based, are more likely to adopt new discovery driven innovations. (Pavitt, 1984) And although many sectoral value chains are international, R&D in certain sectors such as automobiles and wireless telecommunication has been found to evidence an explicit home country bias (Cohen et al. 2009). National innovation systems perspectives advance the importance of country-level differences in organization and procedure, which help in better understanding the knowledge-based strategies of firms, the linkages of companies within the national system, and the type of commercialization strategies that are developed. Shapira et al (2011) find that national innovation system characteristics are important in the commercialization of nanotechnology.

One way to assess variations in technology adoption is in terms of the length of time from discovery to application. Science-based technologies are often considered to require a lengthy period of time from initial work in the laboratory through to commercial activity in the business sector. Cockburn et al (1999) note concerns about the long delay between science-driven discoveries in the biomedical area and adoption of these discoveries by the pharmaceutical industry. They find that the delay is associated with prior internal science as well as the types of products offered. Grupp (2000) describes how lasers underwent a science-driven phase, followed several years later by a technology phase. The second phase saw a significant period of decline and retrenchment (e.g., bankruptcies), followed again by market-driven production. Learning mechanisms underlie these phases in the transition from large lasers to semiconductor lasers. Schmoch (2007) suggests that the length of time between science and commercialization represents a “double boom” in which the first cycle is propelled by technological prospects and the second by marketing prospects. Schmoch observes that scientific trends generally lead technological trends by several years. The work of Grupp (2000) and Schmoch (2007) in particular suggest that the time lag between science and commercialization suffers from challenges faced in initial waves of growth in successfully reaching realization in the market.

The traditional (and earlier) linear model presents a contrasting framework to the double boom concept. The linear model posits that research, development, manufacturing, and market phases are moved through in a sequential manner. Although this model has been criticized for overlooking feedback loops and external linkages, the linear model still remains prevalent in corporate processes and policy models (Rothwell cited in Hobday 2005). A variation to both the linear and double boom models is the concept that science-based innovation proceeds through contemporaneous advancements in research and commercialization. Takeuchi and Nonaka (1986) observe that ever-shortening product cycles necessitate simultaneous rather than sequential development. Under this concurrent framework, we might also expect a significant level of patenting, a common measure of commercial activity, to occur alongside scientific discoveries rather than several years after these discoveries. As Mowery (2011) indicates, we are in a "pro-patent era" in which high rates of patenting are encouraged in universities and other research-intensive institutions as well as in companies.

These differing approaches are reflected in national R&D and innovation strategies. Many established R&D and innovation policies follow a linear model. For example, federal funds in the US are conventionally made available to sponsor basic research in universities and federal laboratories, with the private sector assumed to be responsible for developing this research and applying it to downstream applications. Yet, this traditional model is embedded in an R&D and innovation landscape where non-linear and more complex approaches are also evident. In the US, there is also significant federal and state policy support for public-private research partnerships, private sector R&D tax credits, innovation centers, small business innovation support, technology transfer, and other lateral and cross-cutting mechanisms of public support for applied R&D and commercialization. In particular, concurrent features are evident in the design of US National Nanotechnology Initiative (NNI). The NNI concurrently promulgates these four goals: "(1) advance a world-class nanotechnology research and development program; (2) foster the transfer of new technologies into products for commercial and public benefit; (3) develop and sustain educational resources, a skilled workforce, and the supporting infrastructure and tools to advance nanotechnology; and (4) support responsible development of nanotechnology."[1] It is an approach underwritten by the 21st Century Nanotechnology Research and Development Act (P.L. 108-153). Passed in 2003, this legislation seeks the integration of societal concerns into nanotechnology R&D. While societal concerns include environmental, legal, and ethical issues, the Act also embraces economic development considerations by "ensuring that advances in nanotechnology bring about improvements in quality of life for all Americans." Policy and programmatic strategies pursued by the NNI under the aegis of P.L. 108-153 aim to shorten research-to-commercialization cycles and support accompanying human capital, societal assessment and governance mechanisms so that economic development and societal outcomes from public R&D investments may be experienced sooner rather than later. To be effective, these policies need to stimulate companies not only to engage in knowledge discovery but also to translate new nanotechnology knowledge into usable (and responsible) applications.

Our literature review highlights contrasting generic models – linear, concurrent, and double boom – of how discovery transitions into commercial activity. It is this appropriate to ask: under what circumstances will one or another of these models be most likely to prevail? It is plausible to expect that technical characteristics combined with industrial, market, policy and innovation systems contexts will influence the particular pathways taken by a specific new technology. While game-based models imply that firms may delay adoption until a technology reaches a certain threshold, this may not be the case with graphene, where products reflecting incremental improvements are rapidly being prepared for the market. Indeed, diverse commercialization strategies are likely to be pursued given the wide scope of potential uses and

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[1] http://www.nano.gov/html/about/home_about.html, accessed April 15, 2011.

markets for graphene-enabled applications. At the same time, the commercialization of graphene applications in any particular market is influenced not only by the technical advancement of features related to that application but also by multiple other factors including the ability to scale up manufacturing, progress in competing materials, access to intellectual property and finance, and path dependencies that may present obstacles to deployment. In the realm of electronics, for example, preliminary research efforts focusing on graphene as a silicon replacement are prominent (Van Noorden, 2011). Moore's Law, first conceptualized in 1965, states that the number of transistors in an integrated circuit doubles every two years. As the density of transistors reaches its physical limits using conventional silicon technology, exploring and exploiting higher-performing materials such as graphene is important. Thus, in addition to optimistic profitability forecasts, limitations of current technologies (e.g. silicon) and the existing massive investment in them (including multi-billion dollar fabrication facilities) may attenuate the threshold at which firms decide to adopt the new technology or engage in information seeking activities.

Corporate publishing and patenting are two indicators of private sector engagement with technology and associated investment activity (Shapira et al., 2003). These measures are not without well-known limitations. Corporations do not publish all they know or may delay the release of publications so as to protect intellectual property and knowledge advantages. Publications may also be viewed more as indicating research rather than development activities. Corporations may choose not to seek patents for discoveries, keeping them as trade secrets, or may patent without necessarily having the intent to commercialize these inventions. Nonetheless, with these limitations in mind, evidence from corporate publications and patents can usefully be analyzed to signal what might be the technological and commercialization interests of companies in emergent fields. In the context of uncertainty and information seeking, scientific publishing suggests that companies are developing knowledge and capabilities and also exploring a new technology's utility and viability. Corporate patenting suggests that companies are generating or acquiring inventions that ex ante have potential significance for subsequent market applications and which promise value, be it through the intent to self-develop the new technology, through making it difficult for competitors to develop the new technology in the same way, through licensing, or by increasing the attractiveness of the company to external investors. These are not necessarily mutually exclusive objectives.

If extensive publishing output can be viewed as a penchant for exploration, with patenting seen as signaling an interest in exploitation, then the relationship between these two measures is of interest. Strategic management literature identifies the importance of both exploration and exploitation (see March, 1991), with recent research streams emphasizing the advantages of pursuing both at the same time (i.e. ambidexterity) (e.g. Rothaermel, 2009; Lavie et al. 2010). Pries and Guild (2011) describe the commercialization of innovative technologies from universities as a process consisting of technology, product, and business development activities. Technology development focuses on the science and design of the technology whereas product development incorporates those features into a solution to customer problems. Business development identifies, secures, and orchestrates the complementary assets needed to manufacture and sell products.

Firms in a particular technology domain may concurrently operate in one or more of these development cycles, depending on the firm's existing competencies and perceptions of the technology's value. High publishing output may indicate a firm's investment in technology development and information seeking, which reduces uncertainty and sets the stage for future commercialization efforts. Along the same lines, patenting reveals a firm's emphasis in business development, suggesting that a firm exhibits more confidence in a technology's commercial application. Abstaining from publishing or patenting could signal overt waiting or even complacency. Firms in this last category may view graphene R&D as untenable given the costs and/or lack of in-house absorptive capacity. Such firms are not studied in further detail here.

This study specifically aims to explore the timing and characteristics of graphene corporate activity based on publications and patents. We examine graphene publications and patents over time to understand whether any of the three key models previously discussed are being pursued. A linear model would be evidenced by a substantial lag between research publications and patenting activity; a concurrent model would be evidenced by a simultaneous or at least a much-reduced lag between publication and patenting activity; and a double boom model would be evidenced by a substantial downturn after an initial increase in corporate publication and patenting activity.

Method

This analysis is based on the development of databases of graphene-related publications and patents associated with companies. We identify records in which the company is addressed as an author or a co-author of a publication or as an inventor or assignee of a patent. As noted, limitations exist in using publications as a measure of science and patents as a measure of commercial activity. It would be ideal to have data on graphene-related products introduced by firms. However, as yet, it is too early in the research and commercialization cycle of this novel material for any significant product applications to appear on the market. The use of corporate publications and patents is common in investigating emerging technologies that are not fully at the product stage, which is the case with graphene, and thus is employed here.

Graphene publications were drawn from the Web of Science's Science Citation Index in October 2010, with an update occurring in February 2011, and represent the time period 2000-2010. Interviews with graphene researchers informed us that articles with graphene in the title were most apt to be in domain, whereas articles with graphene in the abstract, but not the title, would capture more less-relevant works. Hence, we restricted our search to title fields. Graphene patents were selected from Thomson Reuters Derwent Innovation Index in April 2011 and represent the time period 2000-2010. Guidance from patent experts led us to use a broader criterion for selection of graphene patents that includes a patent if the term graphene appears in abstracts and claims as well as title. These definitions resulted in 4,787 graphene publications and 911 graphene patents in the 2000 to 2010 period. Most of these patents (97%) are applications, but although they are not granted, they do give an indication of the types of commercial application interests foreseen by the companies that are involved.

Our analysis focuses on the diffusion of graphene across time, countries, and applications. After an initial year-by-year overview of the diffusion of graphene publication and patenting activity, we focus on five multi-year time periods: 2000-2002, 2003-2004, 2005-2006, 2007-2008, and 2009-2010. This multi-year approach is presented to smooth fluctuations that occur in year-by-year analyses in an emerging field that has grown rapidly from a very small initial base. (A test using three-year time periods finds results that are consistent. We thus use mostly two-year periods to allow a greater number of data points.) Our analysis explores diffusion pathways that represent linear, concurrent, and/or double boom trajectories.

Results

The analysis begins with an examination of the trajectory of graphene publications and patents in comparison with fullerene, another nanoparticle that was recognized by the Nobel Prize. Compared with fullerene, graphene has experienced a faster upward trajectory of publications and patents (see Figure 1, which includes all graphene-related publications and patents, not just those associated with companies). After a mid-1980s breakthrough, fullerene publication counts totaled fewer than thirty a year until 1990-1991, when they rose to nearly 350 and eventually tripled in the next two years. By the time the Nobel Prize was awarded in recognition of the work on fullerenes, the fullerene publication growth rate had flattened. Graphene publication counts experienced a 13.5 fold increase from the 2004 breakthrough to the 2010 Nobel Prize award and have yet to level off. This lack of leveling may in part be due to the earlier Nobel Prize recognition of the graphene related work than was the case for fullerenes (six years for graphene versus 11 years for fullerenes respectively). Patenting pattern upswings (including both patent applications and grants) also show similar patterns and differences between the two nanoparticles. There were nearly 16 times more graphene patents in 2010 (the graphene Nobel year) than in 2004 (the graphene breakthrough year). This same figure for fullerenes was nearly 3 times (although from 2000 to 2010, the number of fullerene patents nearly quadrupled). On the other hand, both particles are similar in that once a steep increase in publications began global patent activity follows about two-to-four years later. The double boom phenomenon can be observed in fullerene patent and publication trajectories but not as distinctly in graphene patent and publications trajectories. It is unclear whether the graphene activity has had less history to present a definitive double boom trend or whether graphene will continue to attract ever more scholarly and commercial interest.

[INSERT FIGURE 1 ABOUT HERE]

The broader picture of the growth of graphene provides a backdrop for our focus on corporate publication and patenting activity in the graphene domain. Corporations account for 3% of graphene publications (as authors or co-authors) and 35% of graphene patents (as assignees). Even though companies make up but a small share of all graphene publications, these company-authored papers are very collaborative. Eighty-seven percent of company-authored papers with graphene in the title also have a university co-author. For all fields of nanotechnology in Georgia Tech's global nanotechnology database (Porter et al 2008), the company-university co-authorship percentage is 67%. More than 90% of graphene publications with a corporate co-author and 65% of graphene patents assigned to a corporation were published since 2006. The top companies based on number of graphene publications (through to the end of 2010) are IBM (32), NTT (12), AMO Gmbh and NEC (nine each), and Alcatel Lucent (eight). The top corporations in terms of patents are Samsung (32), Sandisk 3D (23), Teijin (21), and Fujitsu (17).

In this analysis, we look at the relationship between graphene publications and patents to understand the nature of the lag between the two. Graphene corporate and academic publication and patent activity (which includes mostly universities, but also government laboratory and other research institutions) is presented on a log scale to enhance comparability (Figure 2). The figure indicates that the initial 2000 to 2004 time period saw higher levels of corporate patenting and academic publishing (growing by 43% and 17% respectively) but a four-fold (i.e., 200%) growth in academic patenting, albeit from a small base of four academic patents in the first three years of the decade and 12 patents in the next two years. A second period since 2004 reflects the rapid growth of publishing, even in the corporate sector. Academic publishing was 45 times larger and corporate publishing 28 times larger in 2007-2008 than in 2003-2004. By 2007-2008, corporate publishing and patenting were on level terms. During this middle period, academic and corporate patenting still grew significantly – by 450% for academic patenting and, after a decline in the 2005-2006 period, 87% for corporate patenting – but at a slower rate than that of publishing. In the most recent two years (2009-10), academic and corporate patenting activity once again rose more substantially (by more than 590% for academic patenting and more than 290% for corporate patenting). In sum, graphene has undergone different growth phases. The middle of the decade is dominated by publishing growth, followed by patenting growth at the end of the decade.

[INSERT FIGURE 2 ABOUT HERE]

In the following section, we break down these overall metrics by country and application area. The initial country breakdowns for the top 10 countries ranked by graphene patenting activity are shown in Table 1. The table shows that the US maintains the largest share of graphene patents and publications overall. Other countries are notable for their relatively higher share of corporate patents, for example Japan and the UK. However, compared with the UK, South Korea has a far higher number of corporate graphene patents and holds third place by this absolute measure after the US and Japan. In addition to maintaining a high share of corporate patents, Japan also leads the ten countries in terms of corporate involvement in publications, with many large corporations (e.g., NTT, NEC, Toyota, Fujitsu, and Mitsubishi) publishing graphene research. While UK companies maintain a signficant share of patent applications, they are as involved in publications (Table 1). China's graphene publication and patent data suggest another distinctive model, with more university-led activity in both patents and publications. Patenting participation is stronger in the university than the corporate sectors in China. Highly-ranked countries in graphene patenting do not necessarily rank as high in publication, for example, Finland and Australia rank in the top ten countries for graphene patenting but rather lower for graphene publications.

[INSERT TABLE 1 ABOUT HERE]

We further examine the trajectory of patents and publications for the US and Japan, which have graphene publication and patenting activity throughout much of the last decade. US academic graphene publications grew rapidly from 2003-2008 and US academic patents had a steep trajectory throughout the ten-year period (Figure 3). US corporate patents moved downward between the first two time periods, moved upwards in the middle of the decade, and grew even faster in the last time period. Japan's academic activity showed a more modest growth rate, while Japan's corporate patents and publications demonstrate three distinct waves: early growth to 2004, decline to 2006, followed by a further period of growth to the end of the decade. Between the 2007-2008 and 2009-2010 time periods, corporate patents in the US grew by a factor of 3.8 and in Japan by a factor of 2.5.

[INSERT FIGURE 3 ABOUT HERE]

Company involvement in a science-driven area is not evidenced solely through publication and patent records. For example, corporate involvement also occurs through the sponsorship of graphene research. When examining US-authored publications, we see that the Semiconductor Research Corporation (SRC) consortium is the fourth largest funder of graphene research (after the National Science Foundation, US Department of Energy, and Office of Naval Research); this position is measured by the counts of articles that acknowledge the SRC as sponsoring the work on which the articles are based. Intel also is a relatively significant funder as are foundations (e.g., Robert A. Welch Foundation). In addition, R&D programs in countries outside the US are also among the top funders including China (e.g., the National Science Foundation of China and 973 Program), Germany (Deutsche Forschungsgemeinschaft), European Union, and Korean Government.

With recognition of the limitations of using publication and patent records, we are able to estimate "corporate entry" (Shapira et al, 2011) into graphene by merging the publication and patent databases. Merger of this information yields a global list of 210 companies involved in graphene research and invention through to 2010. The 2000s saw an expansion in the number of companies entering into the graphene domain either through authoring scientific publications or seeking patents (Table 2). Up to 2004, Japan was the early leader by the number of companies involved with graphene, and has continued to be a strong player. The 2000-2002 time period saw the entry into graphene of Japanese companies NEC and GSI Creos; 2003-2004 saw the entry of Sony, Matsushita, Nissan, NKK, and Toyota; 2005-2006 saw the entry of Teijin and Fujitsu; 2007-8 saw the entry of NTT, Casio, Mitsui, Stanley Electric, Tokai Rubber, Toshiba; and 2009-2010 saw the entry of Mitsubishi Chemical, Sekisui Chemical, Toyoda, and Vico. The US had a few companies enter into the graphene domain before 2007 including 2000-2002 with DuPont, BP Amoco, Fullerene Int., Materials & ElectroChemical Research Corporation; 2003-2004 with MeadWestvaco; and 2005-2006 with IBM, Nanodynamics, Nanosource, Supracarbolic, WaveBand Sierra. After 2006, there were many more US corporate entries, exceeding the number in Japan, including 2007-2008 with Dow, Nanoconduction, and Unidym; and 2009-2010 with Sandisk, Texas Instruments, Vorbeck, Northrop Grumman. Korea had no corporate entries until 2007-2008, when Samsung started patenting in the graphene domain along with Sodiff Advanced Materials and N. Baro Tech. In 2009-10 Korean firms Sang, Toray Advanced Materials, and Eichituon entered the graphene domain. Germany saw most of its corporate entries occur in 2007-2008 (AMO, Daimler Chrysler, Danubia NanoTech, Nanofilm Technology) and 2009-2010 (DIC Berlin, KME Germany, Siemens, Tyco Electronics), the exception being Dilo Trading (entering in the 2000-2002 time period). The UK's corporate entries occurred in 2007-2008, including Graphene Ind. Ltd, Hexcel Composites, Carben Semicon, Sci Technology Res Partners, and STREP (Solarprint entered in 2009-2010). China did not have any corporate activity through patenting or publishing until 2009-2010, at which time several Chinese-based companies became involved in graphene: Longhai Naite Chem, Shanghai Aowei Technology Dev Co, ABB Res Ltd, and Tianjin Pulan Nano Technology.

[INSERT TABLE 2 ABOUT HERE]

The types of applications associated with graphene corporate activities suggest diverse use potential. There are prevalent applications related to fuel cells, sensors, and composite materials. To systematically probe potential uses, we use factor analysis to map groupings based on similarity of mentions in the patent abstract. The results in Figure 4 indicate six clusters: (1) screens/displays for computer devices, (2) semiconductor memory chips, (3) biomedical related detection devices, (4) batteries, (5) filler, coatings, and ink, and (6) materials. Some of the application keywords fall in multiple factors, for example, coating. These six clusters represent 69% of the patent records, although some patents involving composites, paper, and optics were not statistically incorporated into these six clusters. Although the electronics industry is prominent in some of these application areas (especially screens/displays, memory chips, batteries), we also see diversity in applications in materials, coatings, and the biomedical area.

[INSERT FIGURE 4 ABOUT HERE]

Materials, filler, and capacitor application areas all grew at the same logarithmic rate (Figure 5). The memory area grew at a slower rate between the first two periods, at a faster rate in the middle of the decade, and at an even faster rate in the last period. The screen area moved upward between the first and second periods, back downward in the third period, then upward again until the end of the decade. The bio area, which is the smallest in terms of patent counts, had the latest but relatively steepest growth, especially from the 2003/4 to 2005/6 periods. Average annual patent growth rates from 2000-2008 were 35% for the textile area, 44% for the filler area, and 39% for the capacitor area. During this eight-year time period, the memory-related patents grew by 63% while screen-related patents rose by 50%. In the last two years, patents in the memory area experienced a more than eight-fold increase, materials saw a 4.8 fold increase, fillers recorded a 4.3 fold increase, capacitor and screen areas nearly quadrupled, and the bio area more than tripled.

[INSERT FIGURE 5 ABOUT HERE]

Corporations are most prevalent in the memory area, where they account for 46% of all patents, and least prevalent in the bio area, accounting for only 31% of the patents. Figure 6 graphs each of the top patent assignees against the application factors presented in Figure 4. Many of the larger electronics companies are active in the battery, memory, detect, and screen application areas. For instance, Samsung maintains a large share of graphene patents referring to the keywords of screen, display, optic, and solar, corroborating other sources of information that indicate Samsung's interest in using graphene for touch screen displays. Besides the large multinationals, there are two SMEs (with fewer than 500 employees) represented in Figure 6. Both firms, Vorbeck and Nanotek Instruments, are US-based and offer two unique characteristics vis-à-vis their larger firm counterparts. Vorbeck's patents appear to cover the full spectrum of the six application factors; the company was the first firm to offer graphene-based conductive electronic inks on the market (Rogers, 2011). Nanotek Instrument's graphene patents, on the other hand, focuses more exclusively in the coating and battery application factors. The finding that smaller firms who patent do so with relatively high intensity is consistent with Brouwer and Kleinknecht (1999) who suggest that once small firms overcome the initial threshold barriers to patenting, they often actively patent to compensate for their lower market power relatively to larger firms.

[INSERT FIGURE 6 ABOUT HERE]

The US has the largest number of patents across all six graphene application areas, but is particularly strong in the memory area. Japan has the second largest number of patents in all six graphene application areas, with particular concentration in fillers. China's patents tend to be in materials, fillers, and capacitors and there is little patent application activity in the other three areas. Korea's patents are most prominent in the capacitor, memory, and screen areas. Germany and the UK have the greatest concentration of patents in the capacitor and filler areas, and (for Germany) the memory area.

Conclusions

This research has shown that corporate activity interest in graphene discovery and exploitation has grown rapidly in leading countries over the past decade. In this paper, we have used publication and patent counts, with a focus on those authored by or assigned to companies, to understand how corporate activity is unfolding in the graphene domain. Graphene research and commercialization are both still at early stages. In the US, as in other key countries, policy has sought to foster concurrent processes of research and commercialization in the nanotechnology domain, which includes graphene.

Our examination of early corporate trajectories for graphene leads to three major observations. First, the discovery-to-application cycle for graphene appears to be accelerated, particularly when compared with earlier discoveries such as fullerene. Even though the emergence of graphene is relatively recent, we do see an upsurge of early corporate activities by large and small firms. Second, there has been rapid globalization, with companies in the US, Europe, Japan, South Korea, and other developed economies engaged in early graphene activities. Significantly, companies in China are now also beginning to enter the graphene domain, building on the expansion of Chinese nanotechnology research capability. Yet, strength in science alone does not guarantee commercial exploitation: the UK, which is a research pioneer in graphene, has a level of corporate patenting slightly ahead of Canada and Germany but significantly lower than in the US, Japan, and South Korea. Third, we see a rapid widening of the potential application funnel for graphene. Corporate patenting trends signal that companies are interested in exploiting the features of graphene in multiple diverse areas including transistors, electronic memory and circuits, capacitors, displays, solar cells, batteries, coatings, advanced materials, sensors, and bio devices. Although graphene was initially touted as a silicon replacement in semiconductors, initial applications are occurring elsewhere, including in electronic inks and additives to resins and coatings. Our analysis highlighted six emerging application areas: displays/screen, memory chips, biomedical related, batteries/fuel cells, coatings and inks, and materials. However, growth patterns differed across these application areas. The display/screen area exhibited the most pronounced double boom growth pattern, the memory area extended upward more consistently, and the biomedical area demonstrated steep and late growth patterns.

In examining corporate engagement in graphene, we sought to understand how early corporate activity patterns related to broader research and invention trends. In traditional innovation models, a lag between research publication and patenting is consistent with the linear model. This is less so with more recent innovation models stressing concurrent launch, open innovation and strategic intellectual property management. In the later case, publication may come after patenting. There are points at which one might also expect an overlap between publication and commercialization, producing a concurrent pattern as research takes place while technological applications are being patented. In our empirical analysis, taking a highly aggregated global view, we found some linearity in that increased activity in general publication output preceded growth in patenting. There is a propulsive effect from the discoveries which subsequently led to the Nobel Prize award, as publications and then patents quickly began to grow. Graphene patents exhibited an upswing about four years after the upswing in graphene research publications. This lag time is apparent for the total set of graphene publications and patents for universities and public laboratories as well as corporations. However, differing patterns were observed when we adopted a more granular look at the corporate sector, which currently holds about 35% of the graphene patents. There is evidence of a double boom in corporate activity, with an initial period of growth of corporate patents early in the decade followed by a lesser rate of growth in the middle of the decade, and resurgence in corporate patenting growth from 2005 to 2010. These changes are relative to what is observed in the dramatic rise in the number of academic publications (and also corporate publications) since 2004. We observed different trajectories by country, with Japan's corporate activity going through more of a pronounced double boom than that of the US. The output of Japanese corporate patents and publications rose quickly but then declined – perhaps signaling Japanese corporate agility in sensing and engaging in new domains, and also subsequent strategic decisions to draw back for a while. But there are also signs of sectoral shifts. In the US, early entry by chemical companies was followed by a decline in activity, then a subsequent wave of corporate activity particularly in the US information technology and electronics industries. Additionally, in the first double boom, there was evidence of concurrent development, with corporate activity occurring in parallel with or shortly after academic activity. This was especially true in Japan, where more than half of its corporations had entered the graphene domain through publications or patents by 2004.

It is to be emphasized again that we are still in the initial phases of graphene commercialization. Nonetheless, the early trajectory of graphene research and patenting reflects the fast pace of growth and change that is seen today in many areas of science-based innovation. Although it is premature to judge the ultimate applications and outcomes of graphene, there does appear to be a shortening of the time lag between research discovery and corporate patenting. The emergence of a wide potential application funnel confirms that graphene has general purpose characteristics and may well have pervasive impacts. Yet, the double-boom fluctuations in corporate activities suggest that it may be more difficult than initially anticipated to successfully embed graphene into commercial applications in certain sectors. Policies to encourage applied research and development partnerships, the scaling-up of production and manufacturing, the availability of finance and other assistance for enterprise innovation, and the assessment of potential health and environment risks are likely to be of ongoing help in supporting companies to successfully and responsibly commercialize graphene.

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Table 1: Top ten countries for graphene patents and publications, 2000-2010, ranked by number of patents.

	Patents				Publications			
Country	**Rank**	**All**	**Corporate**	**% Corporate**	**Rank**	**All**	**Corporate**	**% Corporate**
USA	1	376	127	34%	1	1,086	55	5%
Japan	2	194	125	64%	4	286	30	10%
China	3	144	6	4%	2	400	3	1%
South Korea	4	127	48	38%	12	102	8	8%
Canada	5	20	8	40%	10	113	-	0%
Germany	6	16	5	31%	3	297	11	4%
UK	7	13	10	77%	5	215	6	3%
France	8	12	-	0%	7	166	2	1%
Finland	9	5	-	0%	24	34	1	3%
Australia	10	4	-	0%	34	10	1	10%

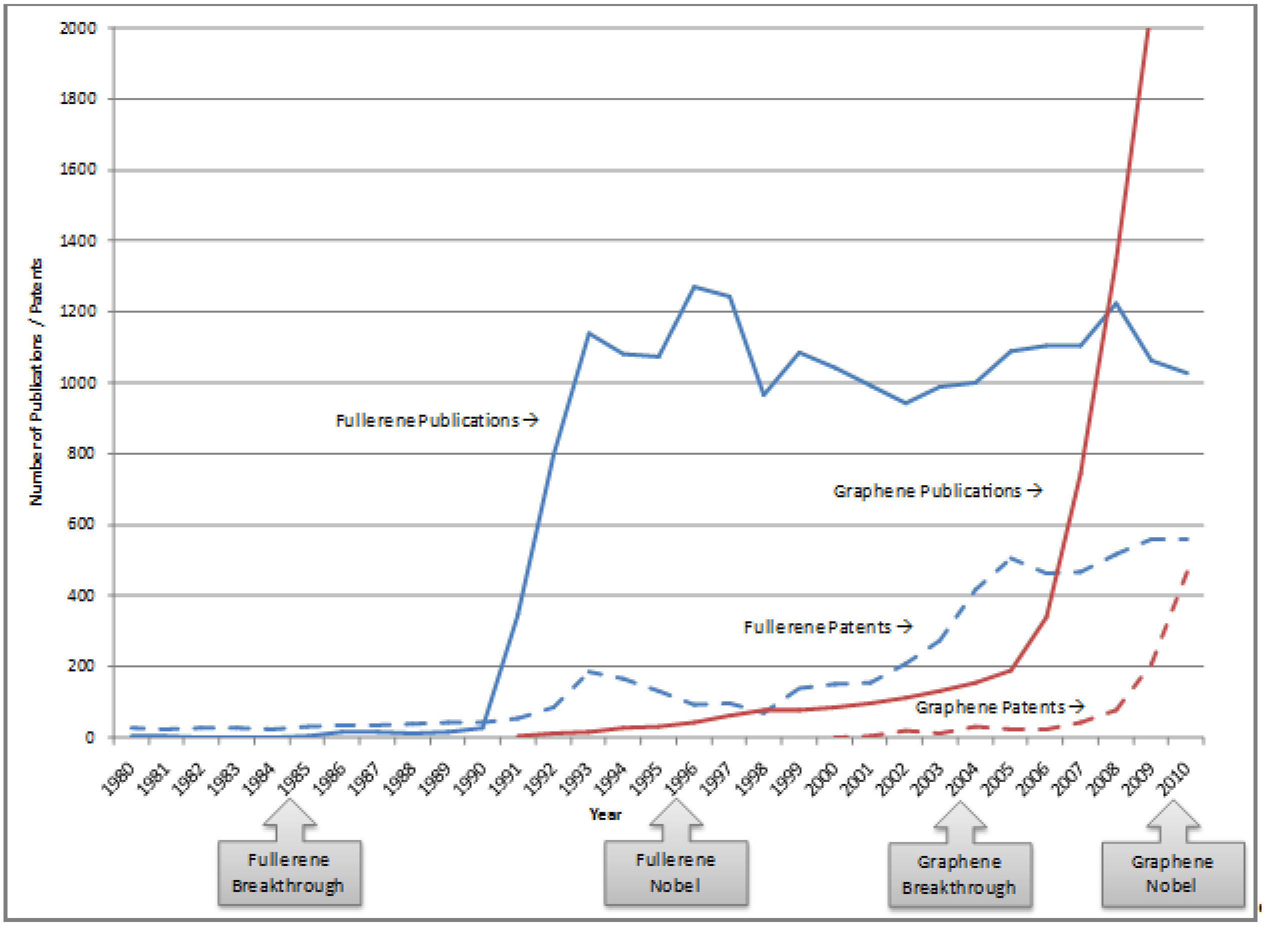
Source: Analysis of worldwide graphene patents (N=874) in Derwent Innovations Index and graphene publications in the Web of Science (N=3,346).

Table 2. Number of companies by first year of entry in graphene publishing or patenting and country, for six leading countries, 2000–2010

	Number of Patents					
Country	**2000-2**	**2003-4**	**2005-6**	**2007-8**	**2009-10**	**Total**
USA	6	1	5	22	37	71
Japan	14	20	4	14	14	66
South Korea				3	4	7
Germany	1			4	4	9
UK				5	1	6
China					4	4

Source: Analysis of 163 corporations involved in graphene publications and patents.

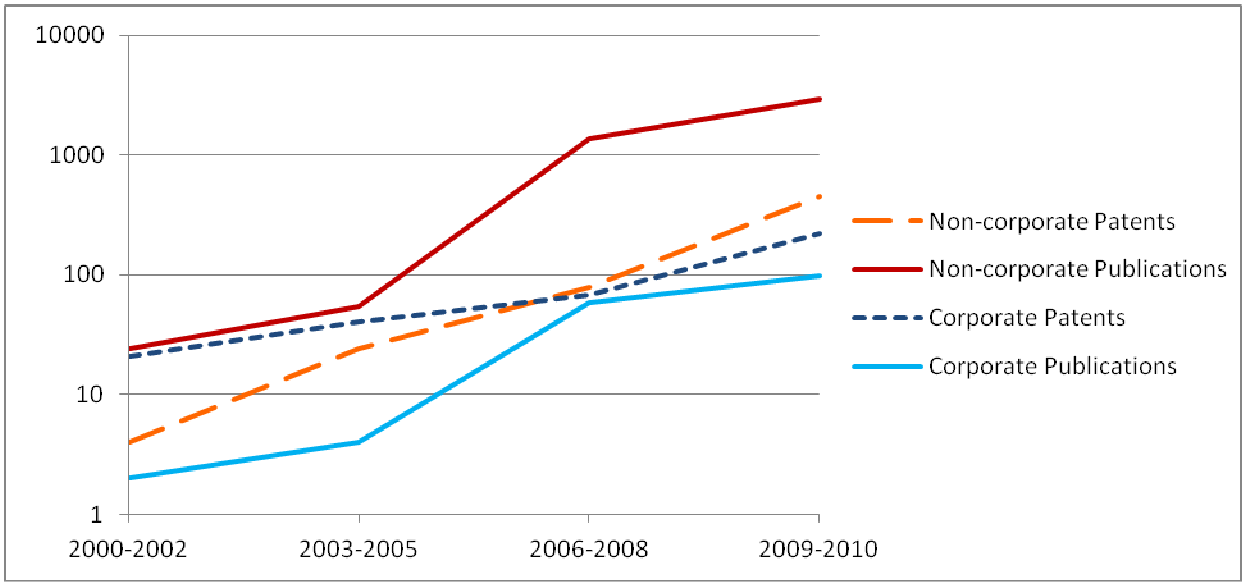
Figure 1. Graphene and fullerene publications and patenting by year



Source: Analysis of publications from the Web of Science for graphene (N=4,787) and fullerene (N=20,701); and patents from Dewent Innovation Index for graphene (N=911) and fullerene (N=5,942).

Figure 2. Worldwide graphene patents and publication trends, 2000-2010

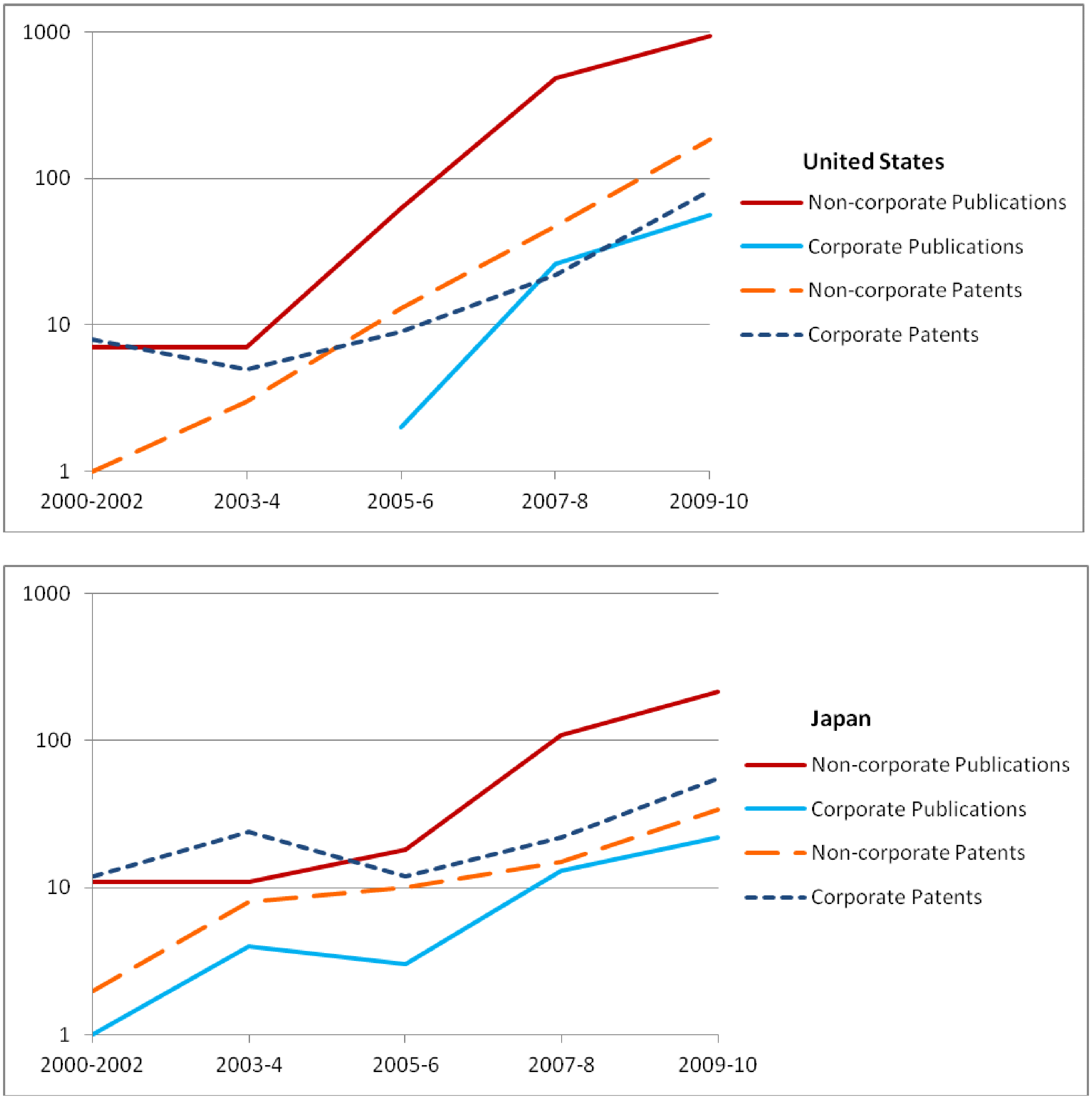
Y-axis = log scaled publication and patent counts



Source: Analysis of of 4787 graphene publications, 911 graphene patents.

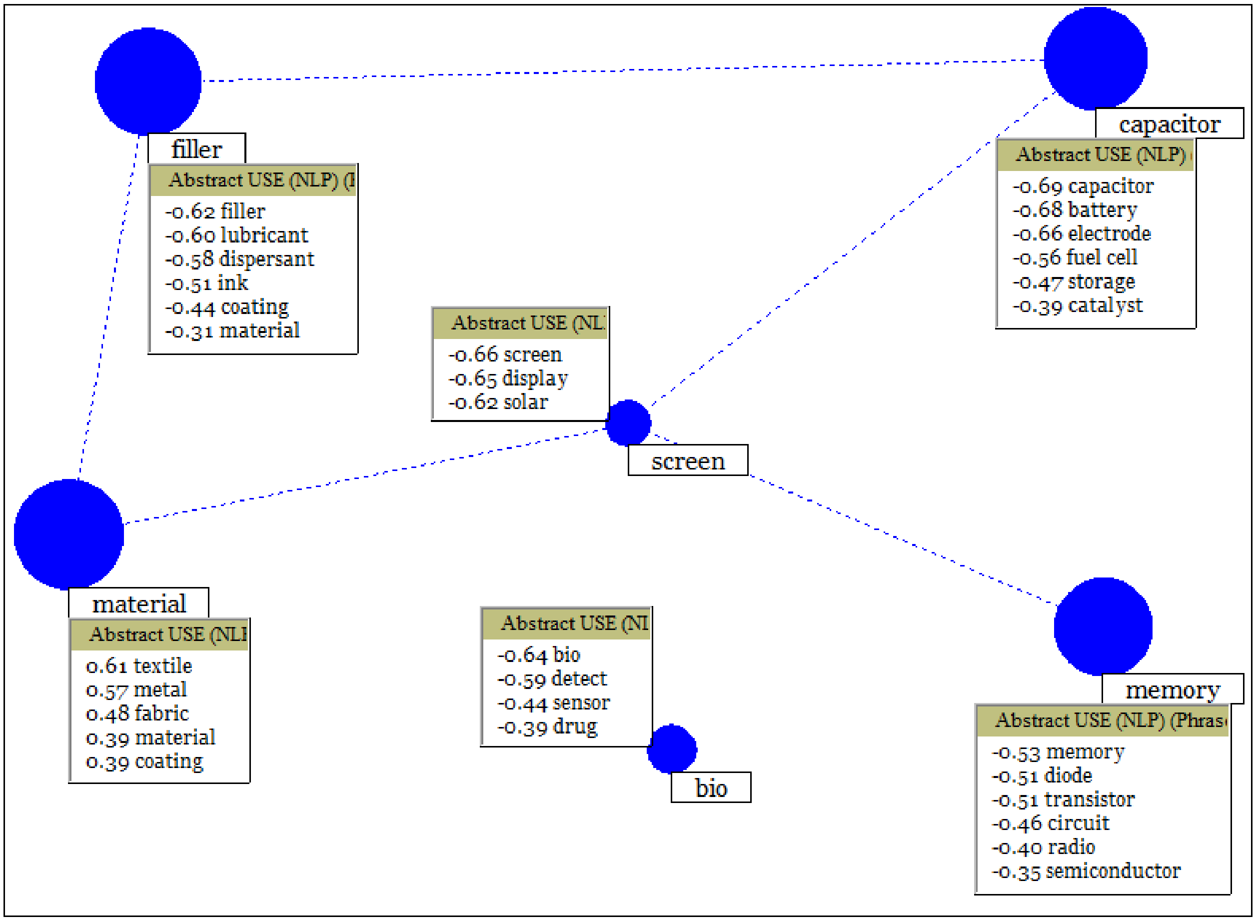
Figure 3. Graphene publications and patent trends: US and Japan, 2000–2010

Y-axis = log scaled publication and patent counts



Source: Analysis of 569 patents and 1,948 publications.

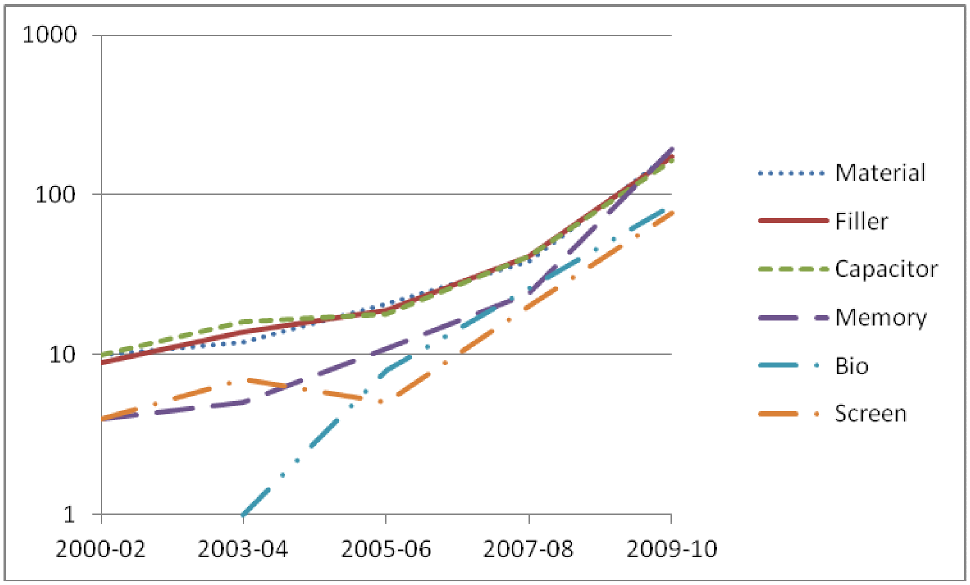
Figure 4. Factor map of graphene keywords in patent abstracts (six-factor solution shown)



Source: Analysis of 633 graphene patents, 2000–2010

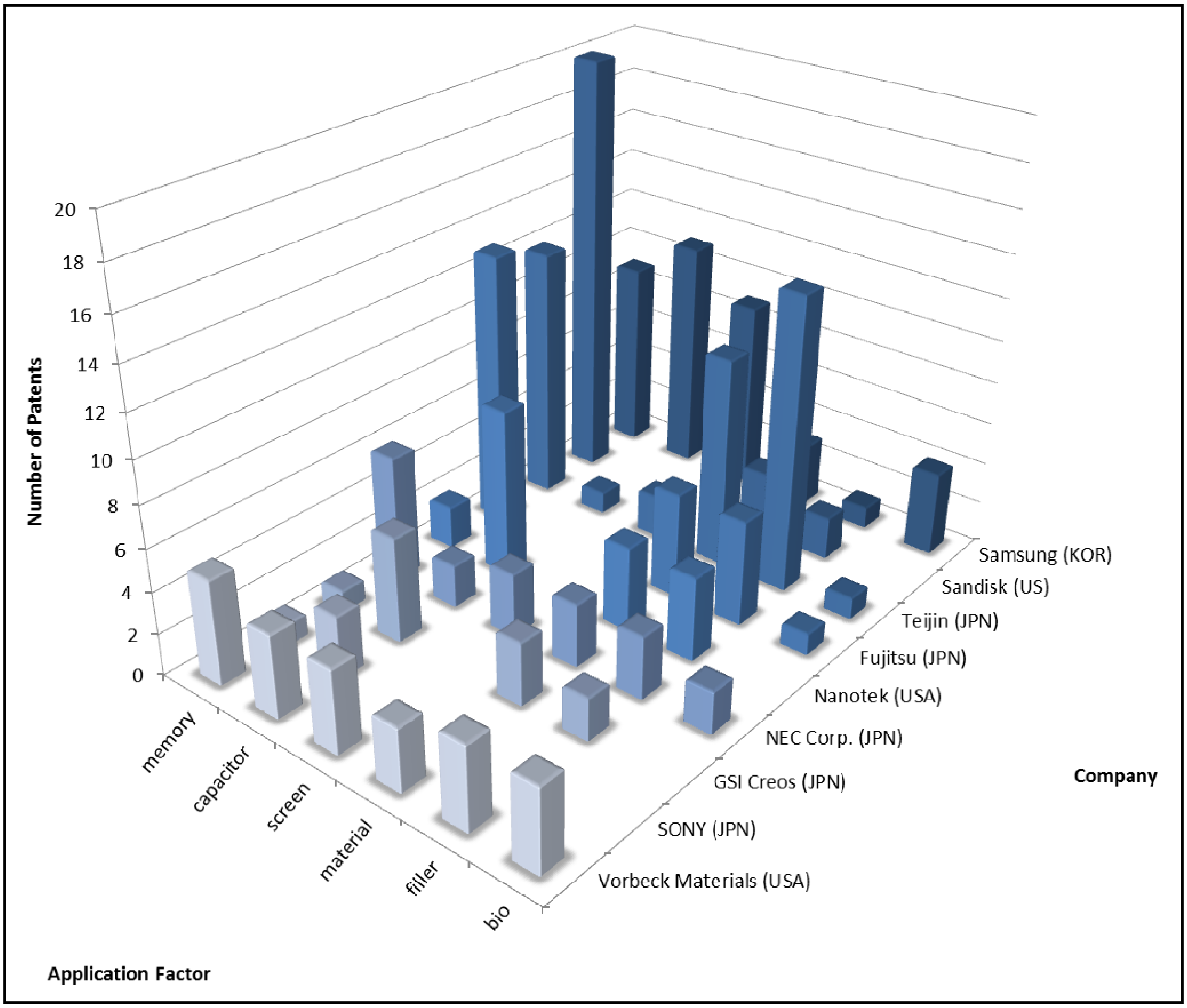
Figure 5. Graphene patent activity by application area, 2000–2010

Y-axis = log scaled patent counts



Source: Analysis of 633 patents.

Figure 6. Graphene application areas in patents of top company assignees, 2000 – 2010



Source: Analysis of 633 graphene patents