Journal of High Technology Management Research 28 (2017) 246–260

Contents lists available at ScienceDirect

Journal of High Technology Management Research

journal homepage: www.elsevier.com/locate/hitech

An Empirical Study of Nanowire Technological Trends

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ARTICLE INFO

Keywords:
nanotechnology
patent analysis
bibliometrics
visualisation mapping
nanowire

ABSTRACT

This paper follows a bibliometric method for nanowire case to make evident the technological trends; to present the relationship between patents; to help the researchers to discover relatively significant patents and to analyse important relationships between patents to identify those with most commercial potential and those which are critical technologies. This research focuses on the nanowire case study due to fact that this field is one of the most mature nanostructures and is one of the highly invested fields in nanotechnology. In terms of methodological approach, this study uses a different patent collection method than previous studies. This new method offers a new taxonomy that could make a significant impact on accurate patent data quests and increase the reliability of the patent analyses. As patent data are valuable sources of technology innovation and for forecasting technical change, this study utilises nanowire patent documents to pick out the technological trends, to identify nanowire technologies which both have the most commercial potential and which are critical at the organisational, national and international levels.

1. Introduction

Nanotechnology is the manipulation and production of nanomaterials and nanodevices at the level of atomic and molecular precision (Ramsden, 2005). Nanotechnology is interdisciplinary, as it depends on the knowledge and expertise found in conventional disciplines such as chemistry, physics, biology, material sciences and medicine (Islam & Miyazaki, 2009). For this reason, there is much varied research being conducted in order to gain insights into this field and to forecast its possible effects.

The focus of this study is nanowires and it aims to shed light on various technology trends and dominant actors by analysing nanowire patents granted up until 2012. The nanowire is one of the most mature nanostructures that are available today and so an analysis of the patents in this field is significant as there are more applications for nanowires and the technology is closer to its commercial exploitation. For this study, 4484 nanowire patents have been analysed and the data covers all the granted patents until March 2012.

Patent data provide valuable sources of information for the purpose of research in innovation and for forecasting technical change (Archibugi & Planta, 1996). Reliable and valid information about a particular technology or innovation system can be gathered if the patent data is analysed systematically (Choi & Park, 2009; Lee, Jeon, & Park, 2011). Some of the reasons why patent analyses are pursued include the discovery of promising technologies, assessment of technological advances and new trends, or to help in strategic decision-making for an organisation (Firat, Woon, & Madnick, 2008). Patent analysis can benefit various individuals and organisations such as inventors, R & D departments, policy-makers, academics and managers. Generally, looking at various patent analyses, the most commonly used methods are bibliometric and statistical analysis; if some of these studies are clustered under various categories, these can then be subjected to network analysis, citation analysis, trend extrapolation/impact analysis, life cycle analysis,

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http://dx.doi.org/10.1016/j.hitech.2017.10.001

innovation system modelling, roadmapping studies and economic base analysis (Chang, Chen, & Huang, 2012; Daim, Rueda, Martin, & Gerdsri, 2006; Guan & Liu, 2016; Johnson & Liu, 2011; Kostoff, Toothman, Eberhart, & Humenik, 2001; Miyazaki & Islam, 2007; Wartburg, Teichert, & Rost, 2005).

This paper follows a bibliometric method to make evident the technological trends; to present the relationship between patents; to help the researchers to discover relatively significant patents and to analyse important relationships between patents to identify those with most commercial potential and those which are critical technologies. This paper analyses the nanowire case at the national and organisational context. The dominant actors, their intentions regarding nanowire technology usage and various nanowire applications are examined.

Although there have been previous studies that used bibliometric studies to analyse patents and focused on implementing nanotechnology related patent documents, these studies did not particularly focus on the nanowire case. In any event, there is a need for up-to-date studies in various areas of nanotechnology, as it is an emerging field undergoing rapid development. Previous studies used a different methodology in terms of collecting patent documents and this paper increases the efficiency of nanotechnology patent analysis as a more reliable patent data collection method is used.

2. An Overview of Nanowire Materials and Applications

Nanowires (also known as quantum wires) are nanostructures less than tens of nanometres long. There is a possibility that silicon nanowires will provide the next architecture for transistor designs. Nanowire transistors can be at least four times faster than traditional silicon devices and could result in high-performance, low-cost, flexible and miniaturized electronic circuitry for many products and applications.

In today's various applications many materials such as steel, plastic and ceramic is greatly used. These types of materials are followed by advanced materials such as; fibers, titanium and silicon as they offer different properties than traditional materials in terms of their mechanic, electrical or thermal properties (Harris, 2009). These materials can be replaced by some prospective materials such as nanowires due to their extraordinary characteristics such as their conductivity level, rapid thermal response or high flexibility. Nanowires are one of the next enabling materials that will reshape the future of various technologies, products and systems. For illustration purposes, the following Fig. 1 is generated.

Nanowires have many current and prospective applications in electronics, optics, magnetics and sensors (Dresselhaus, Lin, Rabin, Black, & Dresselhaus, 2004). Some of these applications are at incremental and radical level. At the present, there are very limited numbers of nanowire related applications and they are at incremental level. However, there are significant numbers of potential applications and some of them are at radical level so some technologies may change or be replaced by nanowire related advancements. Some of these potential applications of nanowires are lie in the magnetic information storage devices (Dresselhaus et al., 2004). By using nanowires, it is possible to increase the capability of storing information in a smaller area and to suppress the onset of the superparamagnetic limit that is important for avoiding magnetically recorded information.

There are many potential applications that are based on silicon nanowires (Shin, 2007). Silicon nanowires will be designed to contour the transistor's channel, surrounded on all sides by a wrap-around silicon oxide, high-K metal gate. These new nanowire transistors will have different characteristics to the most improved FinFET transistors. FinFET transistors have a three-dimensional gate (FinFET/Tri-Gate) while nanowires have a cylindrical shape so the gate can be in multipoint all around the device. Nanosensors are another promising application that will be produced by nanowires. These new nanosensors are likely to be highly sensitive for the detection of single molecules. As nanowires are at a very small scale, when molecules make contact with the nanowires, they will generate a measurable change in the current passing through the nanowires. There are many possible applications for nanowires by using them in nanosensors, one of their important applications being to detect cancer proteins. This would allow cancer tests to be more accurate in an inexpensive way.

Having mentioned potential applications of nanowires, it is essential to mention that commercialization of nanowire related

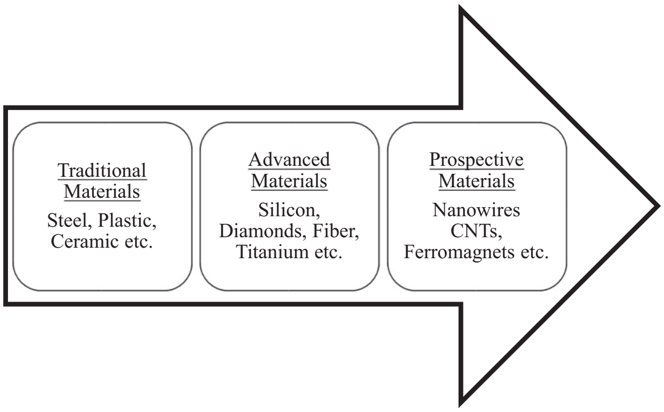

Fig. 1. Advancement of Materials.

applications necessities reliable mass-production methods so these new technologies can be transferred into the industry. One of the biggest challenge in nanotechnology related studies is to identify and categorize possible applications as the field is generally highly diverse. This field needs a deeper examination where related technologies are categorized and possible linkages between inventions and industry need to be enlightened. For this purpose, patents are considered to be a great source to explore and identify key regions, organisations and linkages for nanowire case.

3. Patent Examination and Tech Mining

Patents have a great function in innovation and economic performance by reason of its pivotal role in the development of technology transactions (Archibugi & Planta, 1996; Nelson, 2009). The purpose of patents is to promote commercialisation by authorizing inventors or organisations by law to profit from their inventions (Baldini, Grimaldi, & Sobrero, 2006; Grimaldi, Kenney, Siegel, & Wright, 2011). Patents are regarded as an intersection between inventions and innovations leading to the diffusion of technology. However, the common notion about the function of patents may not be true as it may hinder or support innovation depends on various conditions (Fontana, Geuna, & Matt, 2006; Motohashi & Muramatsu, 2012). For this purpose, the structure of patenting activity should be examined well to understand the related determinants that affect this process.

Between 1985 and 2010, according to the WIPO database, the total number of patents granted globally was almost 14 million and also, there was over 12% growth in 2010 (WIPO, 2011). The growing usage of patents for the purpose of securing inventions by corporate and academic organisations is related to changing patent regimes, innovation policies and large amounts of investment in R & D (OECD, 2004). Technological and scientific developments have created novel movements of innovation, particularly in the nanotechnology field, and patenting practices are highly relied in collaborations between global networks of key actors across different systems of innovation in the regulatory and legislative frameworks of patent systems have led to extensive domains of patentable subjects (Kang & Park, 2012). For example, the patent classifications for nanotechnology were only introduced from 2004 (ETC Group, 2005) and are still in their development stage.

By exploring the changes in a particular patent data, it is possible to evaluate many aspects of technological change. Quantitative analysis on patents is used as measurement for the results of invention and innovation related activities. There are plenty of patent studies that focuses on the association amongst technological advancement and economic progression (Greif, 1992; Hidalgo, Molero, & Penas, 2010; Ma, Lee, & Chen, 2009; Sorek, 2011), or there are some studies which focuses on the research and innovation developments in a countrywide and a global context (Abraham & Moitra, 2001; Encaoua, Guellec, & Martínez, 2006; Faber & Hesen, 2004; Wu & Lee, 2007). There are some researched that concentrated on the viewpoint of corporations strategy to assess the stage of technology development in a particular sector by analysing patent statistics as a guide or a certain technology (Bachmann, 1998; Trappey, Wu, Taghaboni-Dutta, & Trappey, 2011; Tseng, Hsieh, Peng, & Chu, 2011). In some studies the relationship between the key actors analysed within a particular innovation system through the patent analysis (Dangelico, Garavelli, & Petruzzelli, 2010; Tödtling, Lehner, & Kaufmann, 2009; Waguespack & Birnir, 2005).

Camerani and Malerba (2010) found that patent analysis can be used as a one way of identifying patterns in technological entry in different field. They focused on examining the relationship between technological entries and patenting activities of different types of organisations and sectors. Traditional approaches explain that new entrants have mainly profit oriented motivations to involve in a new field. Also, previous studies found entry rates have high correlation with the types of sectors and that high entry leads to better innovation performance (Geroski, 1995). New to previous literature, Camerani and Malerba (2010) identified that share of new entrants highly differs across different countries and sectors and that the higher level of technological turbulence in one field leads to a lower level of repeated patenting by the new entrants and vice-verse. Accordingly, examination of patent documents with regards to persistence development and continuity in increase number of new entrants may indicate the commercial potential of the field. Moreover, analysis on the distribution of number of patent documents may indicate the progress of the field since if the general distribution shows high number of patent ownership by individual organisations then this may indicate lower turbulence and higher innovative potential.

Considering similar methodological approach and similar field by other authors, there are various studies that follow bibliometric studies for patent documents and academic publications. In general, patent analysis by text-mining follow general steps as described by Tseng, Lin, and Lin (2007): 1) task identification by defining purpose of the study, 2) searching and retrieving patent data, 3) cleaning and categorisation of data by turning unstructured data to structured, 4) abstracting by summarizing the key sections of patent documents such as their claims, topics and patent codes, 5) clustering based on some extracted attributes, 6) visualization by various approaches such as heat maps, and 7) interpretation to define trends, technological relations and also foresight technological changes in the chosen field. Yoon and Park (2004), also follows a text-mining based bibliometric study on patent data sets and proposed a methodology adding new network metrics compared to well know metrics such as centrality, betweenness and closeness measures to develop patent networks to be able to generate deeper understanding of the results. Yang, Gao, and Yang (2016) explored the network structure of technology in biotechnology industrial clusters and how prior structure affects formation of ties among technologies from a network perspective. Similar to this, Ozcan and Islam (2014) also found that the structure of innovation networks having great impact on the innovative outputs of organisations and nations. After examining various studies where similar approaches and purposes are used, Table 1 is created to summarize all activities in this field.

As shown above in Table 1, there are application oriented focuses apart from methodological concerns in this field. Porter and Youtie (2009) looked at nanotechnology positions in relation to other disciplines by considering its multidisciplinary nature and addressed the cross-disciplinary linkages in this field. Another similar work was conducted by Miyazaki and Islam (2007), focusing on cross-country comparisons, actors and institutions by using similar quantitative methods (bibliometrics and tech mining) to

Table 1
Methodological and Application Purpose of tech-mining and patent-mining studies (Chiavetta & Porter, 2013; Madani, 2015; Ozcan & Islam, 2017; Porter & Cunningham, 2005).

Analytics, techniques and methodological approaches	Bibliometrics Scientometrics Data mining Text mining Natural language processing and semantic analysis Information retrieval Big data analysis Network analyses Co-occurrence, mapping, clustering analyses Pattern recognition Patent, publication and social media analyses Data visualisation
Purpose and application areas of studies	Emerging technologies and, technology dynamics and trends Technology assessment, forecasting, roadmapping and foresight Technological evolution, diffusion and convergence Technology monitoring and business intelligence Technology process management Innovation analysis Collaborative innovation, innovation cluster and network analysis Absorptive capacity, dynamic capability and knowledge absorption levels Social network analysis Knowledge management R & D and innovation management Engineering and high-tech industries Science and technology (S & T) indicators Science, technology and innovation policy studies Evolutionary economics Technology assessment and impact analysis

understand the sectorial innovation systems in nanotechnology from a global perspective. Shapira, Youtie, and Kay (2011) focused on an overview of corporate entry into nanotechnology through patents and publications and nanotechnology innovation factors in the shift to commercialization. It is also observed that the influence of cross-border international invention linkages suggests that national innovation policies need to be open and international in orientation. Huang et al. (2003) also completed similar work by presenting a longitudinal patent analysis on nanotechnology patents between 1976 and 2002. Their work included content map analysis and citation network analysis by obtaining the required data from individual countries, institutions and technology fields.

The recent work of Song, Kim, and Lee (2017) focused on the development of new technology ideas by using a similar approach with f-term analysis. They found a systematic way of analysing how new technology ideas are generated by combining two technologies. This study was a great example of showing converging technologies and it may allow innovators to obtain new ideas by using their techniques. Similar to this study, Islam and Ozcan (2015) examined the technological linkages by using a tech-mining method to show how different applications and research areas merge together to create new technological domains. Similar to these studies and our study's focus, Kay, Porter, Youtie, Rafols, and Newman (2015) studied another nanomaterial that is called graphene. In their study, they mapped the R & D activities of graphene by using patent data with tech mining and data visualisation approaches. They illustrated the landscapes of graphene science by mapping patent and publication data separately in the same time period to compare understand the insight of R & D activities in this field. Afterwards, authors created overlays for graphene publication and patenting activities to show how the graphene as a material was discovered and used between 2000 and 2013. As part of big data analytics, these types of studies are great way of examining and identifying technological activities in large data sets to give significant information to all actors such as academia, industry and governmental bodies to make better and more informed decisions.

Having mentioned that patent analysis is relatively significant in various contexts, there are also various limitations to these studies. This is due to the fact that not all inventions lead to innovation, and not every innovation has a fundamental influence on technological or economic value. In the nanotechnology field, there are many patented inventions that have not been commercialised and so it is not possible to claim that every nanotechnology related patent will be commercialised. Moreover nanotechnology is a highly dynamic emerging field; the progress of patents, innovations and industry is rapidly changing and this causes even higher uncertainty. It is important to develop methodologies that can explain how patent activity collaborations occur and the interactions of dominant actors that shape this complex system. For this purpose, the methodology of this study offers a new taxonomy in gathering accurate patent data and analysing them to answer the questions proposed.

An examination of previous studies suggests that first of all there is a need for an up-to-date study in the nanotechnology field as it is an emerging field, which is constantly changing. This study fulfils this need by analysing all the nanowire patent documents that are available until March 2012. Secondly, previous studies used a different methodology in terms of collecting patent documents and this paper increases the efficiency of nanotechnology patent analysis as a more reliable patent data collection method is used. Finally, the analysis of commercially promising sub-categories of the nanotechnology field is another factor which differentiates this study from previous studies.

Considering the focus area of this field, this study will use a tech mining method (Porter & Cunningham, 2005) to test following scenarios;

- **Proposition 1.** Nanowire related research areas are expected to have high differences across different regions, actors and sectors due to its interdisciplinary and wide application areas.
- **Proposition 2.** Nanowire related technologies would have dominant actors in specific application areas due to repeated patenting with defensive approach.
- **Proposition 3.** The distribution of numbers of nanowire patents amongst organisations and their relative density by large actors may indicate high commercial possibilities.
- **Proposition 4.** The patenting ratio between academic and industrial actors may indicate the stage of the field in terms of its research or commercial era.

4. Methodology

The present study applies a tech-mining methodology, proposed by Porter and Cunningham (2005), combining bibliometrics using patent abstracts from patent databases. Tech mining analyses relations between actors and technologies within a given innovation system, using specialist keywords, derived from the Nano Science and Technology Institute publications. The subsequent analysis was performed using dedicated tech mining software Thomson Data Analyser (TDA), automating mining and clustering of terms occurring in article abstracts and article descriptors such as authors, affiliations or keywords that are recommended by the Georgia Institute of Technology. The outline of this paper including methodology and the general process can be seen as shown in

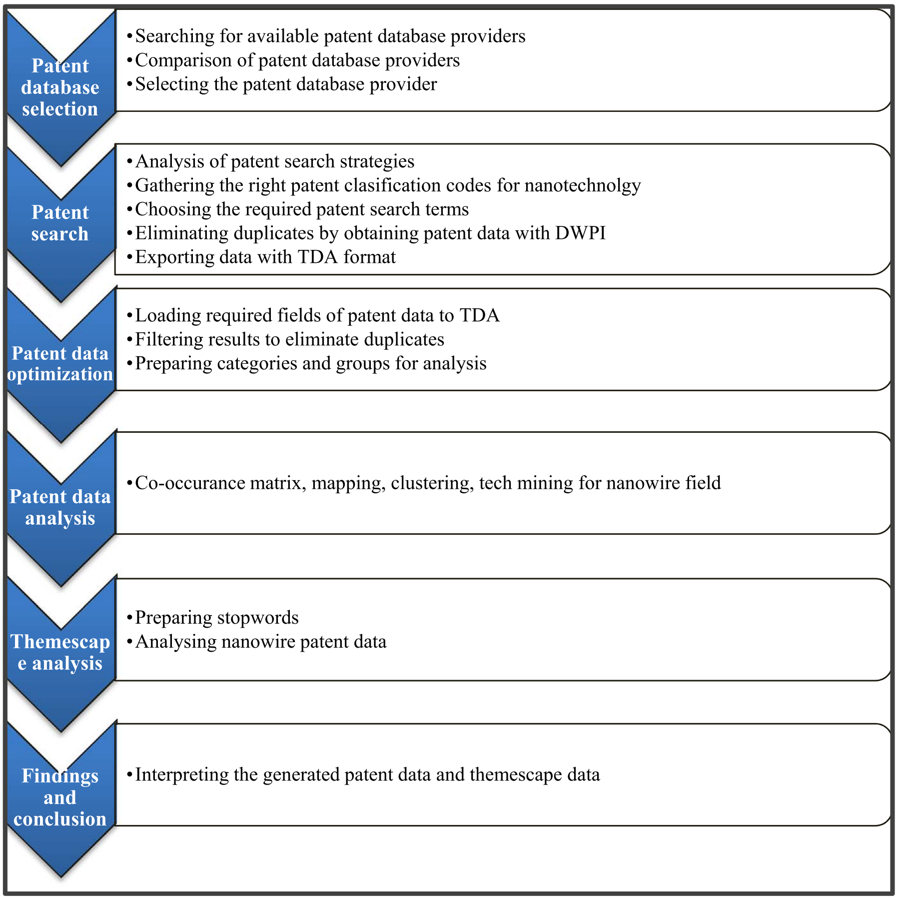

Fig. 2. The Outline of Research Methodology.

Fig. 2. In general, gathering the valid patent data, efficient analysis of large data sets, and handling and interpreting the outcomes of the analysis is crucial for the accuracy of the results.

In addition to the patent analysis by TDA, another offering of Thomson Innovation, namely their Themescape tool, is used. By using Themescape, the key terms are mapped for all available nanotechnology patents. The analysis of a Themescape map was highly supportive for the findings of this study because it allowed the categorisation of documents containing similar content as they were placed near each other on the map. Moreover, the density of documents can be indicated with tall or small peaks and the distance between peaks sheds light on the relationship between content, as peaks that are located closer to each other have more closely related content than peaks that are located farther away. Contour lines indicate relative document density and by using the tool it is possible to zoom in on a specific area whereby new contours, labels, and documents can be revealed. Accordingly, it becomes possible to explain various technological relationships under the umbrella of nanotechnology.

Various approaches are followed by patent analysts and researchers in this field. There are many limitations and drawbacks in terms of the search terms that are used and the nanotechnology patents which are obtained. There are two main approaches in this field. One of the approaches is to use all the required nanotechnology related terms such as nanotube, nanowire and nanosensors in the patent search and to try to get the highest possible hit list as a result. This type of search may be faced by two major problems. The first one is that the researcher may not cover all the required nano-terms and as a result they may not be able to access all the required nanotechnology related patents, for example colloidal crystals, quantum dot and fullerene do not include the term ‘nano’, but they involve nanotechnology related patents. Another issue with this type of research is that there are many patents that mention nanotechnology related materials within patent documents that are not for a nanotechnology invention. For example, if the details of some of the patents are analysed, it can be seen that the nanotechnology related term is used in the description of a non-nanotechnology patent that states the invention can also be used with one type of nanomaterial such as nanotube. As a result, it is possible to include unnecessary patents and exclude necessary patents in the analysed patent data set.

The second common approach in nanotechnology related patent analysis is to obtain all the patents that include terms that start with such terms as ‘nano’ or ‘quantum’ by using Boolean search logic such as nano* OR quantum* and excluding all the unnecessary patents from the result which include terms such as nanosecond and nanometre. The problem with this approach is that there are many nanotechnology related patents that include those terms, for instance there are many nanotechnology patents that include both ‘nanowire’ and ‘nanosecond’. Also, as was explained with the previous approach, there is a possibility of obtaining unrelated patents that mention the possible compatibility of a particular nanomaterial or nanoparticle with the patented invention.

Given the limitations and drawbacks of the above approaches, it was thought that the best nanotechnology search practice would be to use all available nanotechnology classifications to gather all the nanotechnology classified patents such as 977 by USPTO, B82 by IPC, Y01N by ECLA and 3C082 by Japanese F-Terms. All irrelevant patents classified within these categories could be eliminated by using Boolean search logic with very broad nanotechnology related terms, such as ‘nano*’, ‘quantum*’ and ‘fullerene*’. Afterwards, the DWPI (Derwent Patent Index) is used to exclude patents that appeared more than once in the search results, as, due to nature of patent applications, inventions are granted more than once in various patent authorities to secure the invention in that respective country or region. For the nanowire case, the following search terms are used;

$$\begin{aligned}&(\mathrm{AIOE}{=}(\mathrm{B82}^{*})\ \mathrm{OR\ FIC} = (\mathrm{B82}^{*})\ \mathrm{OR\ UCC} = (977^{*}))\ \mathrm{AND}\ (\mathrm{ALLD}\\ &\quad =(\mathrm{nanowire}^{*}\ \mathrm{or\ nano} - \mathrm{wire}^{*}\ \mathrm{or\ quantum\ ADJ\ wire}^{*}\ \mathrm{or\ nano\ ADJ\ wire}^{*}))\end{aligned}$$

As a result 4484 individual nanotechnology patents were obtained for the period from 1970 to 2012. The obtained results were imported into the Thomson Data Analyser (TDA) and, to validate results further, the duplicate results were eliminated and variations of company, inventor, institute and university names were unified where they appeared as separate patent assignees. After the dataset was prepared, various functions were utilized using the same tool, Thomson Data Analyser, to generate the required analysis.

5. Analyses of Nanowire Patenting Trends

There are 4484 patents related to nanowire technology. The patenting activity for nanowire technology started in 1994. There are 8420 inventors, 1619 organisations and 32 countries involved in this field. As shown below in Fig. 3, the peak year was in 2009 with 731 nanowire patent documents. It appears that there has been a rapid increase in the number of nanowire patents starting from 1999 to 2010.

5.1. *Technology Trends of Nanowire*

The highest numbers of nanowire patents are classified under the nanostructure devices that belong to organic semiconductor devices and thick/thin films (see Table 2). The primary attraction of organic molecular nanostructures is their potential low cost and the extreme flexibility that the device engineer has in choosing a material whose properties have been specifically tailored to meet the needs of a particular application. The materials are easily integrated with conventional semiconductor devices, thereby providing additional functionality to existing photonic circuits and components. Active organic nanostructures appear to be on the verge of transforming a large number of optical and electronic applications.

Another density of nanowire patents appears to be in semiconductor nanomaterials that are expected to be one of the revolutionary materials for various industries. The current focus on nanomaterials is not only on the end structures, particles or materials themselves but how to process them and how to produce them efficiently as well. The reason why companies focus on this area is

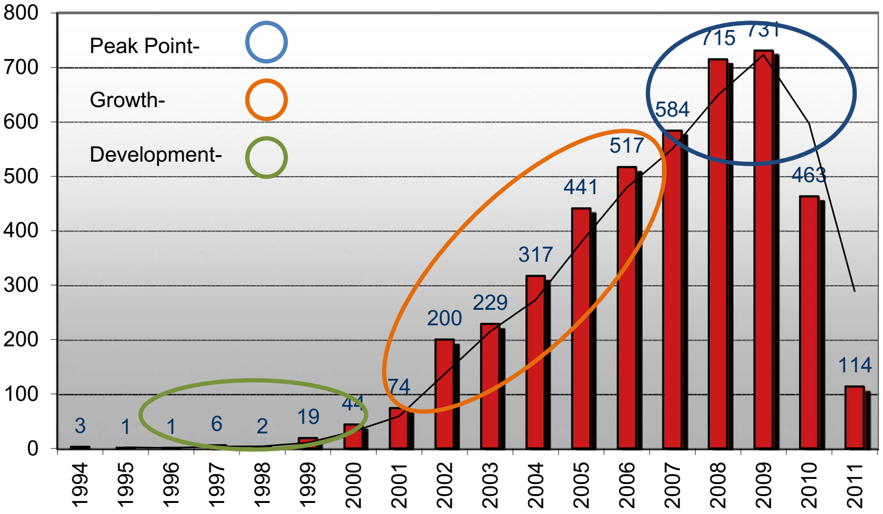

Fig. 3. Number of Nanowire Records per Year.

because once the usage of nanomaterials or nanostructures is increased and it becomes highly commercialised, mass production will be required and this is another problem that needs to be overcome by organisations regarding the commercialisation of the nanotechnology field.

As captured when the nanotechnology field is analysed as a whole, polymer applications appear to be a key field for nanowires as well. There are many researchers working on nanowire-polymer nanocomposites and silver nanowire, as these are the source of materials that will allow companies to increase the efficiency of many electronic components and also it will make radical innovations possible. For example, a Portuguese company Displax has invented an electronic device that can interpret the electrical disturbances in a thin transparent polymer film that is embedded with nanowires. This innovative film can detect any type of pressure on it and identify it as a command. Accordingly, consumers can have a multi-touch interface anywhere as the thin film screen can be used on any non-conductive surface. These kinds of innovative products will usher in the commercialisation era of nanotechnology.

As shown in Fig. 4, patenting activity for semiconductor nanowires starting from 2000 gradually increased and appears to have reached its peak in the semiconductor nanomaterial field. This is due to the patenting activity of large organisations within the electronics industry such as Samsung, and IBM. The top nanowire patenting category that is related to thick/thin films and organic semiconductor devices (U12-B03F2) appears to have started to fall from 2005 (92 patent documents) to 2009 (11 patent documents). This may be due to progress and growing interest in carbon nanotubes, because carbon nanotubes have very similar characteristics to nanowires and also can be produced in different forms as well. Another reason for this decrease may be due to the fact that this subfield of nanotechnology may have reached its peak point where most possible inventions have been made with regard to the applicability of nanowires, and this could be a sign for the commercialisation of nanowires for this particular area. Also, the Proposition 1 appears to be wrong for the nanowire case as there is no high differences in nanowire field due to high concentration of its possible applications in electronics field. It is clear that there is less diffusion and multidisciplinarity in nanowire materials and technologies when it is compared to the nanotechnology field.

5.2. The Distribution of Nanowire Patents

In Fig. 5, the distribution of numbers of nanowire patents amongst organisations and their relative density within the area is presented. In general, it is accepted that mature fields have higher number of patents in the 100 + patent documents range. For instance, a field that is in its initial or development stage would have higher proportion of its granted patents in up to 20 documents range. As explained in the literature review, commercial viability and profitability of a field encourage organisations patent repeatedly. It seems that nanowire technology is at a stage between a developing and emerging technology as the number of patents that are granted to large organisations (101 + documents and 21–100 documents) is increasing, but it is not very significant if it is compared to the whole nanotechnology field and also other mature technologies. The more nanowire patents are granted to large organisations, the higher the possibility of commercial outcomes. Therefore, nanowire technology may be getting close to its highly commercialised stage as stated in Proposition 3 based on its patenting distribution.

5.3. Mapping of Key Nanowire Terms

In the following Fig. 6, the mapping of key technology terms within nanowire patents is shown. It appears that nanowires that act as insulators (e.g., SiO2, TiO2) have the highest patenting activity along with carbon nanotubes. The ability to insulate nanowires opens up new possibilities for nanoelectronics because insulation around the nanowires avoids different ones from shorting each

Table 2
Technology Profile of Nanowire.

Number of Records	753	597	527	526	513	442	338	289	255
Technology Term	Devices and thick/thin film and organic semiconductor devices > Nanostructural devices (U12-B03F2)	Semiconductor materials and processing - > Nano scale structure formation and deposition (U11-C13)	Semiconductor nanomaterials (L04-A05)	Semiconductor materials and processing - > Nano-structural materials (U11-A14)	Polymer applications - > Nanotechnology (A12-W14)	Semiconductor processing – electrodes (L04-C11C)	Electro-(in)organic - > Other manufacture and treatment of electr (on)ic components and materials (L03-J)	Electro-(in) organic - > Batteries, accumulators, thermoelectric elements [unclassified] - > Solar cells (L03-E05B)	Inorganic nanostructures - > Nanotubes, nanorods, nanowhiskers (E31-U02)
Range of Years	1999–2011	2000–2011	2000–2011	2000–2011	2000–2011	1998–2011	1999–2011	2000–2011	2002–2011
Percentage of Records in Last-3 Years	9% of 407	25% of 597	68% of 527	39% of 526	42% of 513	32% of 442	30% of 338	49% of 289	40% of 255
Top Inventors	Duan Xiangfeng [10]; Bando Yoshio [9]; Chunming Niu [9]; Empedocles Stephen [9]; Stumbo David [9]	Kamins Theodore I. [12]; Duan Xiangfeng [10]; Wang Shih Yuan [10]	Bangsaruntip Sarunya [22]; Sleight Jeffrey W. [17]; Cohen Guy [11]	Bangsaruntip Sarunya [19]; Sleight Jeffrey W. [11]; Cohen Guy Moshe [9]	Jang Bor Z. [9]; Zhamu Aruna [9]; Fukuzaki Ryozo [8]; Joo Jin Soo [8]	Park Young Jun [11]; Bangsaruntip Sarunya [8]; Fu Xiao-Jun [8]; Kamins Theodore I. [8]; Li Ming [8]; Park Sang Cheol [8];	Bando Yoshio [5]; Zhu Zi-Qiang [5]; Cho Moon Kyu [4]; Fan Shou Shan [4]; Jiang Kai-Li [4];	Naoi Kenji [13]; Koyama Hirokazu [12]; Takada Hiroshi [11]	Bando Yoshio [6]; Chen Jian-Jun [6]; Gao Lin-Hui [4]; Ye Zhi-Zhen [4]
Top Organiza-ti-ons	HEWLETT-PACKARD DEV CO LP [27]; SAMSUNG ELECTRONICS CO LTD [23]; NANOSYS INC [15]	SAMSUNG ELECTRONICS CO LTD [42]; INT BUSINESS MACHINES CORP [27]; HEWLETT-PACKARD DEV CO LP [26]	INT BUSINESS MACHINES CORP [48]; SAMSUNG ELECTRONICS CO LTD [37]; KONICA CORP [21]	INT BUSINESS MACHINES CORP [44]; SAMSUNG ELECTRONICS CO LTD [33]; COMMISSARIAT ENERGIE ATOMIQUE [18]	SAMSUNG ELECTRONICS CO LTD [22]; UNIV KOREA RES & BUSINESS FOUND [19]; UNIV CALIFORNIA [17]	SAMSUNG ELECTRONICS CO LTD [44]; INT BUSINESS MACHINES CORP [29]; HEWLETT-PACKARD DEV CO LP [19]	UNIV CALIFORNIA [11]; DOKURITSU GYOSEI HOJIN BUSSHITSU ZAIRYO [9]; KOREA ADV INST SCI & TECHNOLOGY [8]; UNIV ZHEJIANG [8]	KONICA CORP [39]; SAMSUNG ELECTRONICS CO LTD [29]; FUJI FILM CO LTD [17]	UNIV ZHEJIANG [20]; DOKURITSU GYOSEI HOJIN BUSSHITSU ZAIRYO [10]; UNIV NANJING [7]
Top Countries	US [229]; JP [69]	US [315]; KR [129];	US [282]; KR [113];	US [289]; KR [101]	US [285]; KR [106]	US [238]; KR [125];	US [127]; CN [96];	US [139]; JP [87];	CN [130]; US [53];

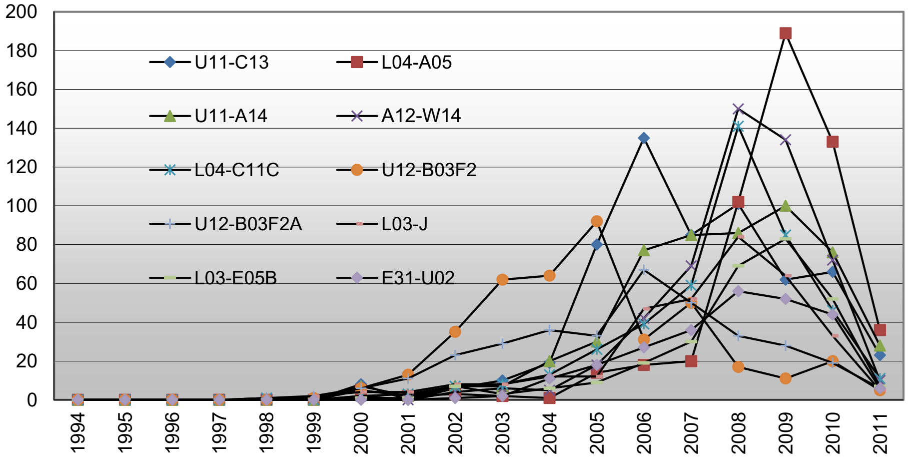

Fig. 4. Technology Trend of Nanowire.

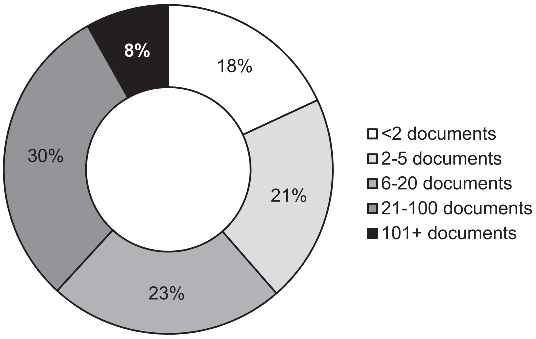

Fig. 5. Distribution of Nanowire Patents by Organisation Activity.

other or conducting each other so the nanowires can be used as the basis of coaxial cables or a simple gating configuration for the production of electronic devices such as transistors. From this point it can be gathered that nanowires can be used for very different purposes within the electronics industry given their possible different characteristics. Thus, researchers are trying to find a way to insulate nanowires so they can be used as connectors of nanoelectronic components.

Another intense research area that is associated with a high number of patent documents and strong linkages with other nanowire technologies is the usage of silver nanowires to prepare flexible, thin, transparent conducting films. At the very low thickness of nanowires, these new films act as networks and at the same time appear to be very transparent with optical transmittance reaching as high as 92% for low thickness. Accordingly, silver nanowires have the potential to surpass the usage of indium tin oxide in LCDs, touch screens, solar cells, and flexible displays and the technology challenges the use of carbon nanotubes as it has some characteristic advantages in various applications.

Looking at the peak point on the themescape map (see below) of catalyst-fuel-cell, which shows how often these words arose in nanowire patents, it is clear that nanowires have become an important structure even in fuel usage. Nanowires are used with new fuel cell catalyst systems to improve the performance of fuel cells. Nanowires form the metal alloy known as a bulk metallic glass, which has a high surface area so that more of the catalyst can be exposed and their activity maintained longer than in traditional fuel cell catalyst systems. This new process may fulfil future energy needs with high number of possible applications in automobiles, computers and electronics equipment.

Degrees-cooling-surface is another peak point that indicates that there are a high number of nanowire patents that are concentrated in a specific field. The reason these words appear among the most frequent is because this is one of the key methods by which nanowire is processed into some other form. The process is to heat a material in a furnace to an extremely high temperature above 1000 °C and then cool it down to around room temperature. By following various processes with the changes that take place at these high temperatures, it is possible to produce different nanoparticles and nanostructures such as nanowires. It is possible to change the size and structure of nanowires or produce nanowires from some other material. The reason why scientists are focusing on this process is because once the size and structure of a nanowire changes then its characteristics change and so it is possible to use the resulting nanowires in different applications or it is possible to increase their efficiency.

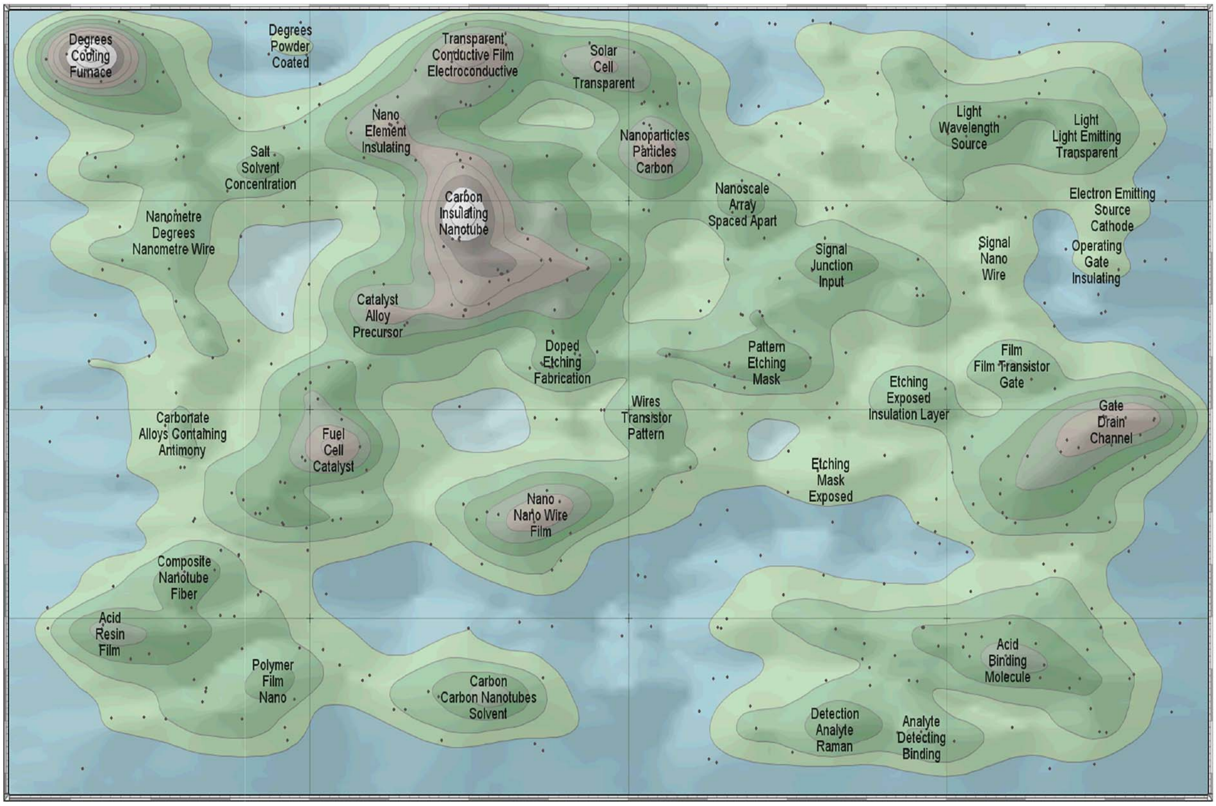

Fig. 6. Themescape for Nanowire Field.

5.4. *Organisational Involvement in Nanowire Patenting Activity*

The leading organisations in the nanowire field are Samsung, Hewlett-Packard and IBM (see Table 3). All the top companies except Hewlett-Packard became involved in nanowire patenting activity after the millennium. IBM have been granted 54% of their nanowire patents within the last three years, which indicates their growing interest in this field in view of the applicability of this nanostructure in the electronics field. This table proves the fact that the key applicability of nanowires is in the electronics industry, as the main patent holders in the field are the top players in that particular industry. The dominant countries for this technology with regard to top organisations appear to be the US and Korea. Examining Samsung's progress, it can be seen that Samsung's involvement in the nanotechnology field started with nanowire technology because even though they are a newer player in nanotechnology compare to other companies such as IBM, only 17% of their nanowire patents have been granted within the last 3 years. As stated in Proposition 2, this field appeared to have dominant actors in specific application areas due to repeated patenting with defensive approach. Especially Samsung appears to heavily prepare themselves for commercialisation and future competition in this field.

As mentioned, the five largest actors in terms of patents use nanowires as a common nanostructure for various purposes. However, to understand the similarities in usage of this nanostructure among these organisations, the similarities in nanowire usage between any of two of the large organisations were calculated. The similarity matrix is based on the technology term items that the organisations have used in their patent documents. The scores are between 0 and 1, with 0 representing no similarity, and 1 representing total similarity. This matrix presents reasonable evidence that almost 50% of patents that are owned by the top 5 organisations are similar in terms of technology terms used. The greatest similarity in nanowire technology terms was found to be between HP, Samsung and Nanosys. The similarities among nanowire patents granted to these giant organisations are due to two main reasons. Firstly, there is a huge amount of collaboration and a number of strategic alliances between these organisations. IBM and Samsung collaborate under the Common Platform Technology and have made a unique contribution to the semiconductor manufacturing process. This collaboration allows various other organisations to create compatibility between their manufacturing facilities and processes in terms of production of various materials at different nano levels such as 32 nm, 45 nm, 65 nm and 90 nm. Accordingly, there is considerable closeness in terms of technology terms used as there are common goals between IBM and Samsung and they heavily invest in research and patents. The second and the most obvious reason is the fact that these five top organisations are all heavily involved in the same industry and so their research focus is similar. Another important fact that stands out is the closeness of nanowire patent terms between the University of California and Nanosys with a similarity value of 0.577. This is due to their co-owned patents and their collaboration in the nanotechnology field (as shown in brackets, there are two co-owned patents). In contrast, there are some cases where the similarity matrix appears very low as in the example of IBM and the University of California.

Table 3
Profile of Nanowire Organisations.

Organization names	SAMSUNG ELECTRONICS CO LTD	HEWLETT-PACKARD DEV CO LP	INT BUSINESS MACHINES CORP	UNIV CALIFORNIA	NANOSYS INC	COMMISSARIAT ENERGIE ATOMIQUE	UNIV SEOUL NAT IND FOUND	UNIV KOREA RES & BUSINESS FOUND
Number of Records	306	184	100	99	78	77	75	73
Top Countries	KR [298]; US [187]; EP [26]	US [153]; WO [38]; EP [5]	US [100]; WO [8]; EP [3]	US [98]; WO [66]	US [77]; WO [31]	FR [73]; EP [17]; WO [8]	KR [60]; US [32]; WO [10]	KR [68]; US [12]; WO [5]
Top Inventors	Lee Eun Kyung [26]; Choi Byoung Lyong [25]; Park Young Jun [17]	Wang Shih Yuan [41]; Williams Richard Stanley [41]; Kamins Theodore I. [35]	Bangsaruntip Sarunya [29]; Cohen Guy Moshe [24]; Sleight Jeffrey W. [21]	Yang Peidong [16]; Jin Sungho [7]; Gruner George [5]; Penner Reginald Mark [5]; Zettl Alexander K. [5]	Chunming Niu [30]; Sahi Vijendra [25]; Stumbo David [22]	Simonato Jean Pierre [9]; Carella Alexandre [6]; Ferret Pierre [5]	Hong Seung Hun [9]; Kim Yong Hyup [9]; Myung Sung [6]	Joo Jin Soo [10]; Ha Jeong Sook [9]; Sung Yun Mo [9]
Year Range	2002–2010	1999–2010	2003–2010	2001–2010	2002–2009	2003–2010	2002–2010	2003–2010
Percentage of Records in Last-3 Years	17% of 306	14% of 184	54% of 100	18% of 99	4% of 78	43% of 77	17% of 75	42% of 73

Table 4
Company Similarity Matrix.

	NANOSYS	CALIFORNIA UNIV	IBM	HP
SAMSUNG	0.587 (0)	0.415 (0)	0.567 (0)	0.614 (1)
HP	0.601 (0)	0.421 (0)	0.473 (0)	
IBM	0.419 (0)	0.261 (0)		
CALIFORNIA UNIV	0.577 (2)			

Note: Numbers in brackets presents the number of co-owned patents.

The low similarity value may be due to the unique technologies that they own (see Table 4).

In Table 5, the patent codes with unique technology terms are listed for each company within the nanowire field. The total number of unique patent codes can be identified next to the organisation's name. It should be clarified that the number of unique patent codes appears to be more than the actual number of patents for each organisation but this is due to the fact that each patent is actually classified under a number of related patent codes. For example, HP owns 184 nanowire patent documents in total (as shown in Table 3) but in the following Table 5, it appears that they have 187 unqiue patent codes.

All of Samsung's nanowire patents were assigned with 394 unique patent codes that are linked to the various technologies within the electronics industry. Even though Samsung's patents have high similarity values in terms of technology terms that are used, Samsung is still the leading company in terms of having the highest number of unique patents. For example, Samsung is the only company that uses nanowire supported catalysts for fuel cell electrodes (× 16-E06A5A is classified as a catalyst in electric power engineering). The aim behind Samsung's 20 patents related to this technology is to effectively use platinum in fuel cells as an electrocatalyst and improve their durability.

As mentioned when the previous table was analysed, there is a lower similarity value between the University of California and other organisations. Table 5 proves that this is due to high number of unique patent codes that they own, as there are 255 unique nanowire patents. Uniqueness of the technology terms that are used for specific patents shows the novelty of inventions as they may represent a new application of nanotechnology in a particular field. In addition to that, higher numbers of unique technology terms show the technological strength of first movers and the way they diffuse nanotechnology in various fields. Having said that, IBM appears to have the lowest number of unique technology terms, which may be due to the fact that they focus on incremental innovation by trying to develop further what is already in existence, or it may be due to the fact that other organisations started learning from IBM and became involved in similar fields.

In Tables 6 and 7 industrial and academic involvement in nanowires can be seen based on their unique and shared capabilities. In Table 6, the section of "academically held nanowire technologies" shows academic actors have unique and diverse capabilities across different fields such as material science, chemistry and medical technologies. Industrial actors have electronics sector oriented focus using nanowire structures as explained in previous sections. This table also shows that the use of nanowires in inks, ink-jet technologies and photodiodes are key areas where they focus on. Looking at very recent academic work, it can be seen that academia also focuses on the applications of nanowires in this field as Duke University scientists found that "Nanowire inks" enable paper based printable electronics by suspending tiny metal nanoparticles in liquids (Stewart, Kim, & Wiley, 2017). This new invention allows to print inexpensive, customizable circuit patterns on just about any surface. The concentration areas where both academic and industrial actors have common patenting categories can be seen in Table 7. As expected, many of these fields appear to be related to electronics field. Table 8 shows recent fields where nanowire related patenting trend occurs by looking at new patenting areas in this field where it has not been done before. To produce this result, nanowire patent data is analysed in time domain checking the date when a patent code appeared for the first time using nanowire term in the patent document. For example, it can be seen that nanowires were being used in manual input devices such as touch screen devices starting from 2010 onwards. Other emerging technology areas can be seen from 2007 to 2011 in Table 8.

Table 5
The Patent Codes with Unique Technology Terms for Each Organisation.

SAMSUNG (394)	HP (187)	IBM (62)	CALIFORNIA UNIV (255)	NANOSYS (175)
X16-E06A5A [20]	S03-E04D1 [10]	U11-C08A6 [8]	B04-F11 [8]	T04-K01B [7]
L03-E04B1 [19]	U21-B01T [7]	U11-C08A5 [6]	A12-W11 L [7]	U14-K01A3 [5]
L03-C02A [13]	U21-B05E [7]	L04-C17 [2]	B05-C07 [4]	U11-C19B [5]
U12-A02A4A [12]	T01-S03 [6]	E31-M [2]	B06-F03 [4]	D09-C04B [3]
T04-F02A2 [9]	U21-C01T [5]	A12-E07C1 [2]	B04-E08 [4]	B05-A03A5 [3]
T04-F02C [9]	L03-G04A [4]	U11-C05B3 [2]	B05-U03 [3]	B12-K04A [2]
× 16-E06A1 [8]	V07-F01A [4]	U12-D02A4 [2]	B04-F10 [3]	V04-X01B1 [2]
V05-A01A3 [8]	U21-C01E [4]	E10-A19B [2]	L03-G10A [3]	U11-C15A [2]
A12-E15 [8]	J04-B01A2 [4]	L04-C11C3 [2]	B04-C03B [3]	V01-B03A1 [2]
V05-D05C5 [8]	T04-G02C [3]	U12-A02A2 [2]	D05-H08 [3]	W02-G05A [2]

Table 6
Industrial and Academic Involvement in Nanowires.

Industrially held nanowire technologies	Academically held nanowire technologies
U14-K01A2B - Three terminal switching elements of LCD [16]	L04-C06B - Semiconductor processing - resists [12]
U14-K01A1C - LCD optical components [11]	A10-D - Condensation polymerisation [4]
U11-C05G1B - capacitor manufacture [10]	B06-F03 - Heterocyclic fused ring with 2 rings - sole heteros S and N [5]
U12-B03C - organic devices that are related to electronic applications.[8]	E05-U01 - Fullerene type cage structures containing hetero atom(s) [4]
A08-D01 - Crosslinkers and accelerators for other polymers [8]	E11-M - Fermentation - processes, apparatus [3]
T04-G02 J - Applications of ink-jet printing technology [8]	E31-B03C - Non-metallic elements, metalloids and compounds (F, BR, I compound) [6]
U12-A01A1 - Semiconductor structure of individual LED [8]	S03-E03E - Electrophoresis [4]
U21-B01T - Electronic switching or gating, characterised by switching device (using nanotubes) [8]	S05-Y03 - Implantable medical devices [4]
L04-E02A - Photodiodes [7]	A11-B02A forming processes - orienting/stretching film [4]
T04-G02C - Ink [7]	B03-L Vitamins [5]

Table 7
Shared Patent Codes by Academia and Industry.

Patent codes that are shared by Industry & Academia
U12-B03A - Thin/thick film transistors (inorganic) [49]
U11-C01B - Chemical vapour deposition of semiconductor layer [39]
U11-A13 - Precursors for deposition process in semiconductor manufacture [30]
U11-C07B Wet-etching for semiconductor manufacturing [31]
J04-C04A - Gas sensors [29]
× 12-D01D – Nanomaterials under cables, conductors, conductive materials [28]
L04-C16A – Annealing in heat treatment of semiconductors [29]
U12-A02A4A - Solar cell electrodes [25]
U11-C03J2A - Annealing semiconductor layer [25]
A05-J12 - Polypyrroles and polythiophenes [25]

Table 8
Emerging Nanowire Technologies.

Year	New Technology Terms
2007	L04-C20B - Encapsulation of semi-conductor device using glass or other compositions [4 of 12]; U11-C02J3 - Doping non-semiconductor layers, insulators, polymers [3 of 10]; V07-F02A - Lenses; reflectors; refractors [3 of 9]; U11-A05B - Substrate materials [3 of 3]; V05-D05C - Cathodes [3 of 3]; S03-C06 - Detecting presence of person or object [3 of 3]; W04-M01P - Power supplies [3 of 3]
2008	L04-A03D - Zinc oxide in a semiconductor material AII-BVI CPDS [5 of 39] × 15-A02C - Solar / photovoltaic panel details [6 of 18]; L03-H04E5 - Ceramic substrates for PCB [5 of 9];
2009	L03-E05B1 - Dye-sensitized solar cells [4 of 9]; A12-W15 - Controlled release [4 of 4]; U13-A01A - IC radiation sensor with photodiode, photoconductor [4 of 4]
2010	W01-C01B8H - Manual input devices based on absolute position, including touch screen [11 of 13]; L04-C12J - Gate insulating layers [3 of 4]; M25-C02 - Dry reduction of ore to metal - methods [3 of 3]; × 15-A05 - Large scale solar power generation [3 of 3]; × 21-B04 - Combination of battery and other source [3 of 3]
2011	L04-C07G - Photoetching [2 of 2]

6. Discussions and Conclusions

In this article, nanowire patent documents were carefully analysed with four foci, which are international, organisational, technological and institutional profiles. In addition, this paper explored different models within innovation system theory and various network and cluster models were examined to form the theoretical basis of the study.

The international profile of nanowire technology provided valuable information, such as key regions, with regard to the number of nanowire patents. This research has also presented country based key technology domains and dominant players within those countries. An interesting outcome was to see the changing trend of countries' involvement in nanowire technology as Asian players in the last year had huge involvement in this area. It appears that South Korea and China are now ahead of Japan and close to the US in terms of the number of nanowire patent documents granted.

With respect to the key actors within the nanowire case, it was found that within the electronics industry ownership of patents is dominated by mostly large organisations. There are two main reasons why there is considerable heterogeneity in nanowire patenting activity. Firstly, large organisations have the capability to provide the huge investment necessary for R & D activities and they are aware of the benefits of nanowire technology in terms of its efficiency and its nature for bringing about incremental innovative characteristics. Secondly, they collaborate with academic organisations such as universities and institutions to benefit from their inventions as well. The second point is not found in every national innovation system, but Korea, the US and Japan appears to have a more effective environment compared to other nations in this case.

This paper also looked at the key emerging technologies that can be gathered from nanowire patents. There are three different areas identified that have the greatest potential for commercialisation. The highest level of patenting activity in the nanowire field was related to insulators. For example, it was shown that nanowires can be insulated in a way so that they can be used as nano level coaxial cables or as a simple gating configuration for the production of electronic devices such as transistors. Another important nanowire patenting field was related to silver nanowires being used to prepare flexible, thin, transparent conducting films. This may be the base for future technology regarding transparent displays, flexible devices and highly efficient electronic equipment.

To summarise the important implications of this study, the following conclusions are listed:

- Nanowire technologies and materials are found to be in high concentration of its possible applications in electronics field.
- There is less diffusion and multidisciplinarity in nanowire materials and technologies when it is compared to the nanotechnology field.
- Nanowire related technologies has different focus application areas where they are controlled by some dominant actors with high number of patenting activities and it acts as a barrier other actors to involve.
- The distribution of numbers of patents and their relative density by large firms indicated high commercial possibilities for near future.
- Majority of patent ownership by industrial actors indicated that this field is closer to its commercial era.
- In terms of country based activities, Asian organisations, especially in South Korea and the Chinese region appear to be having a great impact in the nanowire field and may have many commercial outputs in near future.
- There is a sector concentration in the nanowire field (mainly the electronics industry). However, key capabilities of each country and various organisations were identified and the application of nanowire technology is very varied.
- Key potential technologies in the nanowire case include semiconductor technology and active or potentially active organisations should become involved in this field to gain competitive advantage.

To take this study further, there are many other relationships that can be looked at within nanowire technology. As was mentioned in the findings section, there are some organisation and inventors that hold a high number of nanowire patent documents but the question is whether they are highly influential patents in terms of citations, commercial potential and quality. Accordingly, a follow-up study could be conducted on nanowire patent documents to look at this field in terms of quality in comparison with quantity using citation analysis.

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