Chapter 1 Introduction

1.1 Research Background

Patent is an important type of intellectual property. By publishing the technical details of an invention in a patent, a government grants the inventor the right to exclude others from using the invention to manufacture and sell products based on the patented technology. Patent documents are rich sources of technological and commercial information. They record the nature of the invention, the direction of the technological development, and the activities of the R&D team. These documents also have an important influence on technological innovation and development. Therefore, a patent is not only an expression of technological progress, but also a tool for exploring a technological potential for economic profit.

Patent analysis transfers the data in the patent documents into systematic and valuable information. In other words, it is a useful method that uses these documents to derive information about a particular technology. In general, patent bibliometrics is most commonly used to implement patent analysis (Narin, 1994). Patent bibliometrics uses bibliometric data from patents to perform statistical analysis and citation analysis. Statistical analysis utilizes bibliometric data such as number of patents, country, assignee, inventor and so forth. Then, statistical techniques are used to analyze the bibliometric data. Citations are the counts of other patents or non-patent literature cited in the patent documents. Citation analysis utilizes these citations in patent documents to find the important patents and other science linkages. The aim of patent bibliometric analysis is to find the status, relationship, technological and scientific foundation of the patents being studied. Furthermore, patent network analysis is an advanced technique of patent analysis suggested by Yoon & Park (2004). This method shows the overall relationship among all patents being studied as a visual network. Researchers can comprehend the overall structure of a patent database intuitively and identify the influential patents in the patent network.

In flat panel displays, field emission display (FED) has been one of the major subjects in recent years. The image in FED is created by impinging electrons from a cathode onto a phosphor coated screen, and the electron source in vacuum device consists of a matrix-addressed array of million emitters (Lin et al., 2000; Talin et al., 2001). In addition, the carbon nanotubes (CNTs) are composed of grapheme sheets rolled into seamless hollow cylinders. In 1991, multiwall nanotubes (MWNTs) were firstly discovered by Iijima (Iijima, 1991), and then single-wall nanotubes (SWNTs) were discovered in 1993 (Bethune et al., 1993; Iijima & Ichihashi, 1993; Saito et al., 1993). In recent years, CNTs have been demonstrated to possess remarkable mechanical and electronic properties and exhibit unique physical and chemical properties as being a quasi-one-dimensional material. The electronic properties of CNTs are either metallic or semimetallic, depending on the geometry (Saito et al., 1992). Mechanically, CNTs have high perfection in their structures and highest modulus of all known materials (Treacy et al., 1996). Due to these ideal properties, CNTs are under investigation towards several applications. The field emission electron sources would be industrially the most promising and are nearly within reach of practical use.

When a high electric field is applied on a solid surface with a negative electrical potential, electrons inside the solid are emitted into vacuum by the quantum mechanical tunneling effect. This phenomenon is called field emission of electrons (Saito & Uemura, 2000), and the field emission from an isolated single MWNT was first reported in 1995 (Rinzler et al., 1995). This is because the CNTs possess the following properties favorable for field emitters: (1) a high aspect ratio, (2) a sharp tip, (3) high chemical stability and (4) high mechanical strength. And the field emission characteristics of CNTs have been intensively studied using various methods such as suspension-filtering method, screen-printed process, and chemical vapor deposition for vertical alignment. Due to their excellent electron emission properties, CNTs have a strong potential of applications to electron emission sources, which can be extended further to FEDs. For this reason, the application of carbon nanotube field emission display (CNT-FED) requires the vertical alignment of CNT on cathode electrode as a better electron emitter (Kim et al., 2001).

Recently, patent analysis and its strategic importance in high-technology management are even more highlighted as complexity in the innovation process grows, the innovation cycle shortens, and volatility in market demand increases. The information in patents can be used to realize the subject matter in technological field such as considering patent as the indicators of technology life cycle (Haupt et al., 2007), using patent analysis for patterns of innovative activity in the information and communication technology (ICT) (Corrocher et al., 2007), and employing patent data mapping the technological trajectories in the medical innovation (Mina et al., 2007). Nanotechnology is a key technology for the 21st century (Meyer & Persson, 1998). Furthermore, it is currently one of the major foci of research, development and innovation activities in all industrialized countries (Alencar et al., 2007). It can be implemented in the fields of electronics, information technology, materials, as well as medicine. Nanotechnology-based products have been applied in commercial use (Romig Jr et al., 2007).

Many studies have indicated the use of patent analysis to analyze the field of nanotechnology such as the patenting activities of nanotechnology (Meyer & Persson, 1998; Hullmann & Meyer, 2003), the relationship between nanoscience and nanotechnology (Meyer, 2000; 2001; 2006a; Hullmann & Meyer, 2003), the technological development of nanotechnology (Hullmann, 2007; Wong et al., 2007), the application areas of nanotechnology (Wong et al., 2007), the non-patent literature (NPL) analysis within nanotechnology patents (Leydesdorff & Zhou, 2007), the performance of inventors working in the field of nanoscience and nanotechnology (Meyer, 2006; Bonaccorsi & Thoma, 2007), and the positions of national nanotechnology development (Alencar et al., 2007). Moreover, Gupta & Pangannaya (2000) used bibliometric analysis to analyze the patenting activity in the area of nanotubes and Kuusi & Meyer (2007) used bibliographic coupling analysis to identify the leitbilder (guiding images) of the nanotubes. These studies demonstrate that the patent analysis can be used to explore the field of nanotechnology successfully. Therefore, using patent analysis to analyze the field of nanotechnology has become an important and popular research subject.

1.2 Research Objective

A great deal of attention is being paid now to CNT-FED which represents a new generation of flat panel display (Choi et al., 2000; Nicolaescu et al., 2004). It is called "image display" and it compares favorably with other flat screens technologies in many aspects such as power consumption, view angle, resolution, slimness, operation stability, life time, and response time. Even though CNT-FED has many advantages and potential, currently only small-size sample displays exist, the technology is not mature enough, and some technical bottlenecks needs to be resolved. In addition, CNTs are the emitter materials of CNT-FED. They have the most important positions in the structure of CNT-FED. However, CNTs also have some technical bottlenecks need to be solved such as how to control the alignment of the nanotubes during manufacturing process, how to produce the high purity, quality and unity of CNTs, and how to control the chirality and the growth position of CNTs on a substrate. Therefore, it is necessary to monitor the current states and the future trends of CNT-FED technology and CNT fabrication before the next stage of technological development. This study implements patent analyses to monitor the technological states and trends of CNT-FED and CNT fabrication. Hopefully, the insights of this study can assist researchers in executing and managing research plans for CNT-FED technology and CNT fabrication.

In this study, the patent bibliometric analysis and patent network analysis are used to analyze patents for CNT-FED technology and CNT fabrication. First, we analyze the bibliometric data in the patent documents by using patent bibliometric analysis to find the developmental path and current states of CNT-FED technology and CNT fabrication. Furthermore, we draw network graphs of patents regarding CNT-FED technology and CNT fabrication respectively by using patent network analysis. This method, which uses keywords dealing with patents, has not been used to analyze the technological trends in the field of nanotechnology up until now. We seek to find the overall relationship among the patents and the relative importance of individual patents in the patent network. And then, cluster analysis can be used to cluster all patents in the patent network and confirm the characteristics of the clusters. This information will be helpful to technology package management. Finally, we suggest future directions and trends of CNT-FED technology and CNT fabrication based on the results of analyses.

1.3 Organization of the Dissertation

This dissertation is organized in the following manner as Figure 1.1 shows: Chapter 1 presents the motive and objective of the study. Chapter 2 reviews the relevant literatures. Chapter 3 gives a brief introduction of methods. Chapter 4 shows the results of analyses and the detailed discussion in CNT-FED technology. Chapter 5 shows the results of analyses and the detailed discussion in CNT fabrication. Chapter 6 concludes this dissertation.

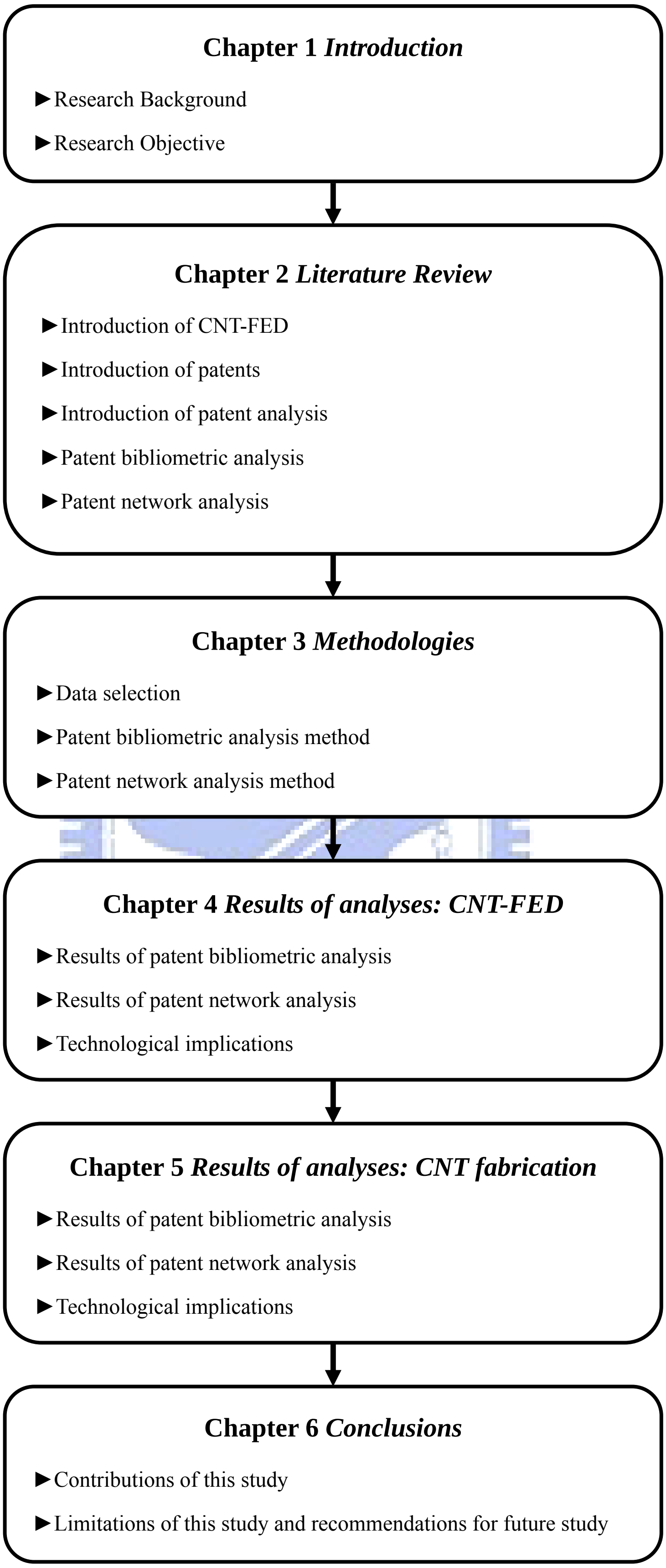


Figure 1.1 Dissertation flow chart

Chapter 2 Literature review

This chapter contains five sections. First, carbon nanotube field emission display (CNT-FED) is introduced. Second, the characteristics of patents are illustrated. Third, the contents of patent analysis are discussed. Forth and finally, patent bibliometric and patent network analysis which used in this study are explained.

2.1 Introduction of carbon nanotube field emission display

2.1.1 Carbon nanotube

Nanotechnology is the development and use of techniques to study physical phenomena and construct structures in the physical size range of 1-100 nanometers (nm), and the incorporation of these structures into applications (Kostoff et al., 2007). In the field of nanotechnology, carbon nanotubes (CNTs) possess important roles and technological paradigms (Kuusi & Meyer, 2007). The formation of CNTs could be traced back to the discovery of the fullerence structure C_{60} (buckyball) in 1985 (Dresselhaus et al., 1996). As figure 2.1, the structure of the buckyball comprises of 60 carbon atoms arranged by 20 hexagonal and 12 pentagonal faces to form a sphere, when the buckyball is elongated to form a long and narrow tube with a diameter of approximately 1 nm, which is the basic form of a CNT (Lau & Hui, 2002).

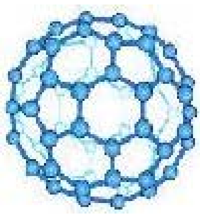


Figure 2.1 Structure of C_{60}
Data source: Iijima (1991)

CNTs are composed of grapheme sheets rolled into seamless hollow cylinders with diameters ranging from 1 nm to about 50 nm. Figure 2.2 shows the structure of a CNT. Two kinds of CNTs, multiwall nanotubes (MWNTs) (Figure 2.3 (a)) and single-wall nanotubes (SWNTs) (Figure 2.3 (b)), are produced by electric arc discharge between carbon electrodes. The diameter of the MWNTs typically ranges from 10 to 50 nm, which the length exceeds 10 μm. For SWNTs, the diameter is only 1nm and the length is up to 100 μm (Saito, 2000). In 1991, MWNTs were discovered in a carbonaceous stalagmite-like deposit by Iijima (Iijima, 1991), which was left on an electrode after the recovery of fullerene soot produced by a carbon arc. SWNTs were discovered in 1993 during the course of synthesizing carbon nanocapsules filled with magnetic fine metal particles (Fe, Co, Ni) (Iijima & Ichihashi, 1993; Bethune et al., 1993; Saito, 1993).

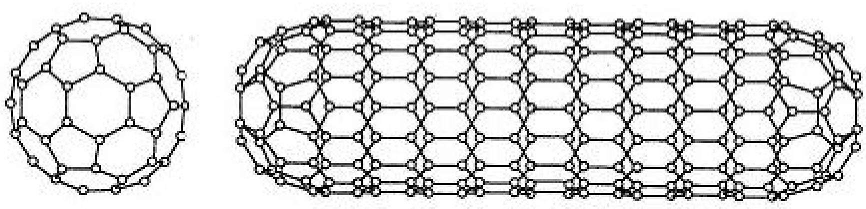
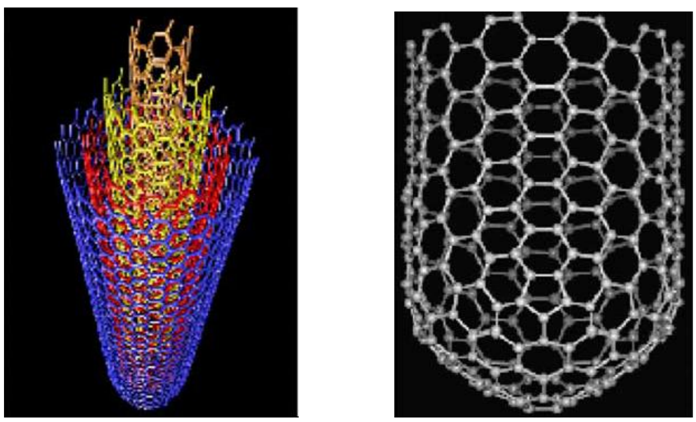


Figure 2.2 Structure of CNT
Data source: Dresselhaus et al. (1996)



(a) MWNT (b) SWNT
Figure 2.3 Structures of MWNT and SWNT
Data source: Kang et al. (2006)

In recent years, CNTs have been demonstrated to possess remarkable mechanical, electronic and thermal properties with providing strong, light and high toughness traits. On mechanical properties, CNTs have high perfection in their structures and highest modulus of all known materials (Treacy et al., 1996). On electronic properties, CNTs are either metallic or semimetallic depending on the geometry (Saito et al., 1992). On thermal properties, thermal conductivity of CNTs is about twice as high as diamond (Thostenson et al., 2001). Due to these ideal properties, CNTs exhibit unique physical and chemical characteristics as being revolutionary advanced materials. Furthermore, CNTs have been proposed as new materials for single-molecular transistors, catalyst supports, electron field emitters in panel displays, molecular-filtration membranes, gas and electrochemical energy storages, energy-absorbing materials, and scanning probe microscope tips (Kuusi & Meyer, 2007).

The fabricating processes of CNTs contain different types of manufacturing technology such as arc-discharge, laser ablation, and chemical vapor deposition (CVD). Arc-discharge and laser ablation techniques for the growth of CNTs have been actively pursued in the past ten years. Both techniques involve the condensation of carbon atoms generated from evaporation of solid carbon sources. The temperatures involved in these methods are close to the melting temperature of graphite, 3000-4000^{o}C. Recent interest in CVD nanotube growth is also due to the idea that aligned and ordered CNT structures can be grown on surfaces with control that is not possible with arc-discharge or laser ablation techniques. And then, the three techniques are discussed as follows.

(1) Arc-discharge technique

Iijima (1991) first observed nanotubes synthesized from the arc-discharge technique. This technique has been developed into an excellent method for producing both high quality MWNTs and SWNTs. As figure 2.4, the arc-discharge technique generally involves the use of two high-purity graphite rods as the anode and cathode. The rods are brought together under a helium atmosphere and a voltage is applied until a stable arc is achieved. The exact process variables depend on the size of the graphite rods. As the anode is consumed, a constant gap between the anode and cathode is maintained by adjusting the position of the anode. The material then deposits on the cathode to form a build-up consisting of an outside shell of fused material and a softer fibrous core containing nanotubes and other carbon particles. To achieve SWNTs, the electrodes are doped with a small amount of metallic catalyst particles (Saito et al., 1996; Dresselhaus et al., 2001; Thostenson et al., 2001).

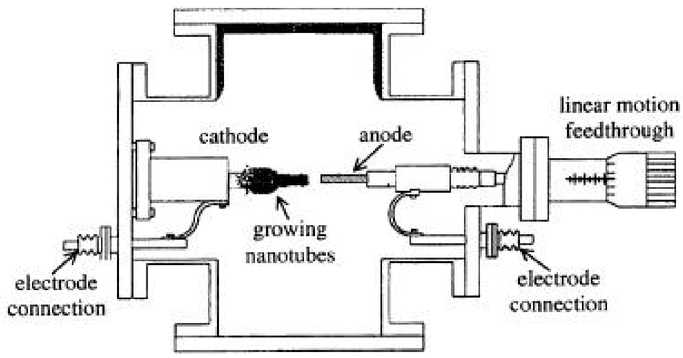


Figure 2.4 Arc-discharge technique

Data source: Saito et al. (1996)

(2) Laser ablation technique

Laser ablation was first used for the initial synthesis of fullerenes. Over the years, the technique has been improved to allow the production of SWNTs. In this technique, a laser is used to vaporize a graphite target held in a controlled atmosphere oven at temperatures near 1200 ^{o}C. The general set-up for laser ablation is shown in figure 2.5. To produce SWNTs, the graphite target was doped with cobalt and nickel catalyst. The condensed material is then collected on a water-cooled target (Collins & Avouris, 2000; Dresselhaus et al., 2001; Thostenson et al., 2001).

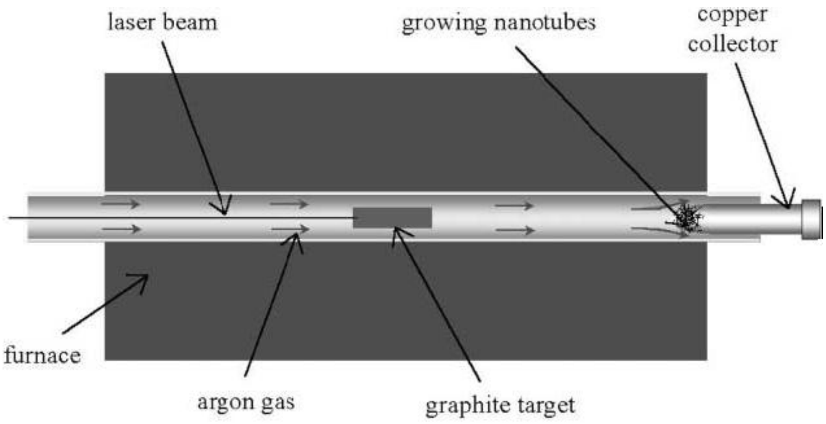


Figure 2.5 Laser ablation technique

Data source: Collins & Avouris (2000)

(3) Chemical vapor deposition

Both arc-discharge and laser ablation techniques are limited in the volume of sample they can produce in relation to the size of the carbon source (the anode in arc-discharge and target in laser ablation). In addition, subsequent purification steps are necessary to separate the tubes from undesirable by-products (Thostenson et al., 2001). These limitations have motivated the development of gas-phase techniques, such as chemical vapor deposition (CVD), where CNTs are formed by the decomposition of a carbon-containing gas.

The growth of CNTs by CVD process involves the catalytic decomposition of the carbon precursor (e.g., carbon monoxide, hydrocarbons or alcohol) on nano-sized transition metal catalyst such as Co, Ni or Fe. Typical CVD temperatures vary between 600 and 1000^{o}C, which are lower than other fabrication methods (Brukh & Mitra, 2006). The general set-up for CVD is shown in figure 2.6. This process is easily controlled by the catalyst structuring, as well as the reaction conditions. The CNTs synthesized by CVD process are known to be longer than those obtained by other processes. It is also available to grow dense arrays of aligned CNTs which are important for the application of field emission devices. However, the process parameter control for the growth of CNT still remains in an empirical manner, because the reaction kinetics and the growth mechanism are not fully understood (Dresselhaus et al., 2001).

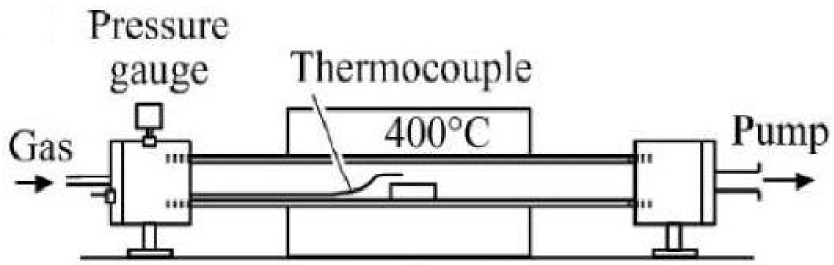


Figure 2.6 Chemical vapor deposition technique

Data source: Kuttel et al. (1998)

2.1.2 Field emission display

The global market for flat panel displays (FPDs) was calculated at 80 billion dollars in 2006. The market is predicted to reach 100 billion by the year 2008, with production totals for thin film transistor (TFT) liquid crystal displays (LCDs) alone to exceed that of cathode tubes (CRTs) by the year 2007 (Funaki & Mochizuki, 2006; Talin et al., 2001). Up to the present, LCDs account for roughly 75% of the FPD market, and other types of FPDs are also increasingly finding their way to the consumer requirements, such as plasma display panel (PDP), field emission display (FED), liquid crystal on silicon (LCOS), digital micromirror display (DMD), organic light-emitting displays (OLEDs), and polymer light-emitting displays (PLEDs). The FPD technologies continue to attract investment because they hold the promise of surpassing LCDs in price, performance, and scalability and own the advantages of low radiation, light weight, low power consumption, and less thermal loss.

The FED is a vacuum electron device, sharing many common features with the vacuum fluorescent display and the Cathode Ray tube (CRT), and the image in FED is created by impinging electrons from a cathode onto a phosphor coated screen. Figure 2.7 shows the working mechanism of FED is similar to CRT except the electron gun in CRT is replaced with millions of emitters. The different between FED and CRT lies in how electrons which excite phosphors are generated and delivered to the anode. In the FED, the electron emitters instead of a big electron gun impinge directly to anode under an enough electric field. Thus, the product of FED can be thinner than CRT in depth.

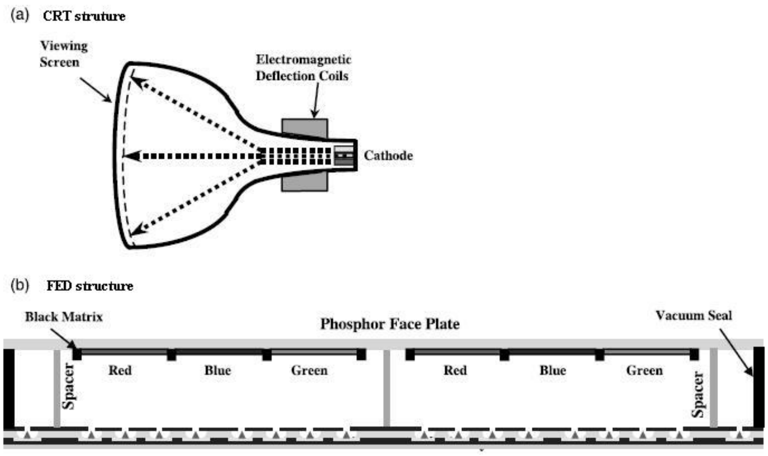


Figure 2.7 Working mechanism of CRT and FED

Data source: Talin et al. (2001)

When a high electric field in the order of 10^7 V/cm is applied on a solid surface with a negative electrical potential, electrons inside the solid are emitted into vacuum by the quantum mechanical tunneling effect. This phenomenon is called field emission of electrons (Saito & Uemura, 2000). Figure 2.8 and 2.9 shows the structure of FED. The electron source in FED consists of a matrix-addressed array of millions of emitters. This field emission array is placed in close proximity (0.2-2.0 mm) to a phosphor faceplate and is aligned such that each phosphor pixel has a dedicated set of field emitter. In addition to the anode and cathode, a FED contains ceramic spacers to prevent the structure from collapsing under atmospheric pressure, a frame coated on both sides with low-melting glass frit, a getter used to remove residual gases inside the package row and column drivers, and an anode power supply.

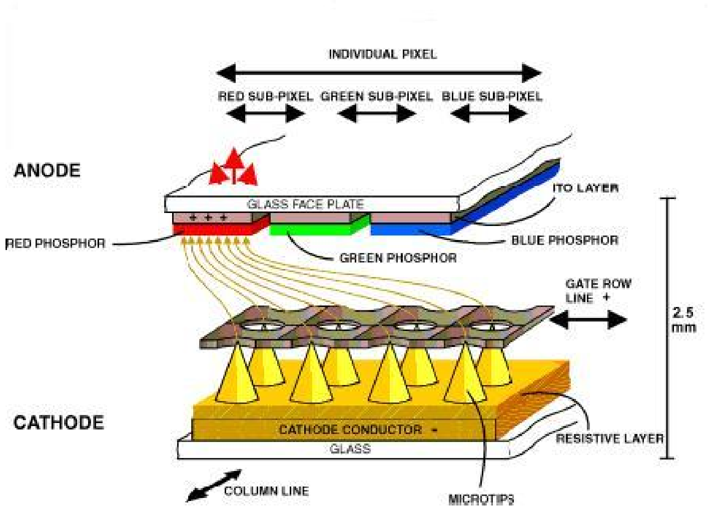


Figure 2.8 Structure of FED — Ⅰ

Data source: Werner (1997)

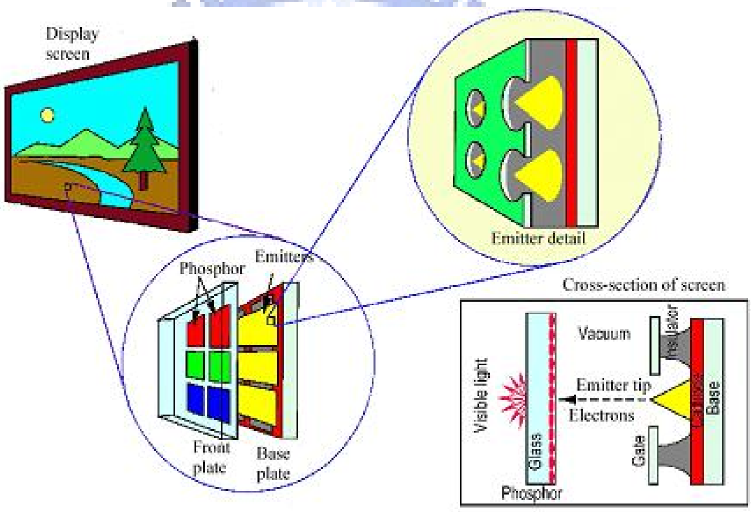


Figure 2.9 Structure of FED — Ⅱ

Data source: Werner (1997)

2.1.3 Carbon nanotube field emission display

According to above mention, CNTs possess ideal properties and propose as new materials for many applications. Among these applications, CNTs for field emission electron sources would be industrially the most promising and are nearly within reach of practical use (Figure 2.10). The field emission from an isolated SWNT was first reported in 1995, and the field emission from a MWNT film was reported in the same year (Rinzler et al., 1995). This is because the CNTs possess the following properties favorable for field emitters: (1) a high aspect ratio, (2) a sharp tip, (3) high chemical stability, and (4) high mechanical strength. And the field emission characteristics of CNTs have been intensively studied using various methods such as suspension-filtering method, screen-printed process, and CVD for vertical alignment. Due to their excellent electron emission properties, CNTs have a strong potential of applications to electron emission sources, which can be extended further to FEDs. Thus, this application is named for carbon nanotube field emission display (CNT-FED). Figure 2.11 shows the prototypes of CNT-FED. CNT-FED possess characteristic of superior display performances such as fast response time, wide viewing angles, wide temperature range of operation, CRT-like colors, ultra slim features, low cost, low power consumption, etc.

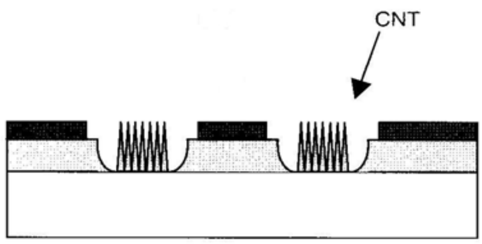


Figure 2.10 CNT-based emitters

Data source: Lee et al. (2001)

Figure 2.11 Prototypes of CNT-FED

Data source: Lee et al. (2001)

CNT-FED requires the vertical alignment of CNT on cathode electrode as a better electron emitter (Lee, 2001). From figure 2.12, CNT-FED is composed of a cathode plate with nano-emitter arrays, an anode plate with phosphors, and standoff spacers. A profile control of the emitted electron beam in the narrow gap is a main issue in designing CNT-FED. Beam control does not only determine CNT-FED structure without cross talk between pixels, but also spacer materials and processing, and phosphor materials and screening technologies for the application of either low voltage or high voltage extraction. Thus, the mutual relationship among the technologies including nano-emitters phosphors, spacers and getters need to be studied. The challenges for the realization of commercialized CNT-FED are the reliability, processing cost, and in situ growth of CNTs on a supporting substrate with good emission characteristics (Chuang, 2005).

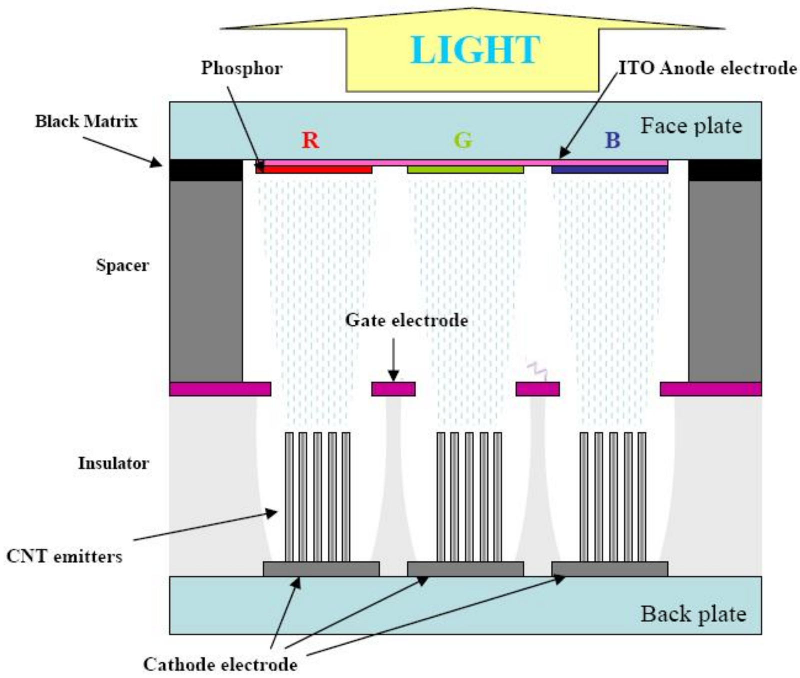


Figure 2.12 Structure of CNT-FED

Data source: Chuang (2005)

2.2 Introduction of patents

This section contains the definition of patents and the types of patents. The detailed contents about these issues are discussed as follows.

2.2.1 Definition of patents

Patents are major outputs of research and development, and represent the origin and features of a new technology (Choi et al., 2007). They describe the nature of inventions taking place in a field of technology, the emerging research directions, and the companies and research groups active in the field (Gupta & Pangannaya, 2000). Hence, patents are rich sources of technical and commercial information. The information is important in the sense that much of the technical contents of patents are not published elsewhere.

According to the definition of World Intellectual Property Organization (WIPO), a patent is an exclusive right granted for an invention, which is a product or a process that provides a new way of doing something or offers a new technical solution to a problem. A patent provides protection for the invention to the owner of the patent. The protection is granted for a limited period, generally 20 years. Table 2.1 shows the definitions of patents from several prior studies.

Table 2.1 Definition of patents

Prior studies	Definition
Milgrom & Roberts (1986)	Patents are important information that enables knowledge to transmit to competitors.
Mogee (1991)	Patent are public information that provide a wealth of detailed information, comprehensive coverage of technologies and countries, a relatively standardized level of invention, and long time-series of data.

Hufker & Alpert (1994)	A patent is a contract between an inventor and the government, whereby in return for full public disclosure of an invention, the government grants the inventor the right to exclude others for a limited time from making, using and selling the invention.
Bronwyn & Ham (2001)	Patents may play a role in facilitating technology- intensive or information-intensive transactions.
Cooper (2002)	A patent enables the owner to prevent others from making, using, importing, offering for sale, or selling the invention claimed in the patent.
Thomas (2003)	A company can use patents to protect inventions that are novel, useful and non-obvious.

On the basis of above mention, the definition of patent in this study is explained as follow. “Patent is an important type of intellectual property. By publishing the technical details of an invention in a patent, a government grants the inventor the right to exclude others from using the invention to manufacture and sell products based on the patented technology.”

2.2.2 Types of patents

There are different criterions of classification in the types of patents. Cooper (2002) proposed two types of patents, which cover different aspects of an invention, including utility patents and design patents.

(1) Utility patent

Any person who invents or discovers any new and useful process, machine, manufacture or composition of matter, or any new and useful improvements may obtain a utility patent. Utility patents may be obtained on mechanical devices, appliances and electrical circuits, and chemical processes.

(2) Design patent

Any person who invents a new, original and ornamental design for an article of manufacture may obtain a design patent. A design patents is directed to the ornamentation of a product.

Kowalski et al. (2003) suggested three types of US patents, including utility patent, design patent, and plant patent.

(1) Utility patent

Utility patent may be granted to anyone who invents or discovers any new and useful process, machine, article of manufacture, or composition of matter, or any new useful improvement thereof. A utility patent covers the way something 'works': an apparatus, machine, composition, etc.

(2) Design patent

A design patent, by contrast, protects the exterior appearance of an article of manufacture (i.e. the way an invention 'looks'). A picture, a print or an impression, however, are not articles of manufacture and, therefore, unpatentable.

(3) Plant patents

Plant patents may be granted to anyone who invents or discovers any distinct and new variety of plants. The plant must be invented or discovered in a cultivated state and asexually reproduced.

2.3 Introduction of patent analysis

This section consists of three parts including the definition, applications and methods of patent analysis. The detailed contents about these issues are discussed as follows.

2.3.1 Definition of patent analysis

On the basis of above discussion, patent documents contain important information for technology management. They record the nature of the invention, the direction of the technological development, and the activities of the R&D team. Moreover, patent information is more current and available in contrast to the information published in the scholarly articles or research journals (Ernst, 1998; Gupta & Pangannaya, 2000). Thus, patent documents have long been recognized as a very rich and potentially fruitful source of data for the study of innovation and technological development (Choi et al., 2007).

However, how to transfer patent data into valuable information? Patent analysis is a good answer. Patent analysis is a novel scheme that transforms patent data into useful information or intelligence. By employing such a technique, the original contents of patents can be converted into valuable information in terms of technological competitiveness, trajectory of technology development, and correlated patent claims (Liu & Shyu, 1997). In other words, patent analysis is a valuable method that uses patent documents to derive information about a particular technology (Daim et al., 2006). The information is helpful to evaluate technological development, explore technological trends, manage R&D process, and make technological plans. Therefore, patent analysis has long been considered as a useful vehicle for technology management.

2.3.2 Applications of patent analysis

The applications of patent analysis are very extensive. It can be applied in various areas and different levels. Ashton & Sen (1988) classified the applications of patent analysis into five areas including technology competition analysis, new venture evaluation, patent portfolio management, R&D management, and product area surveillance. The contents of five areas are described as follows.

(1) Technology competition analysis

Patent analysis can be used to compare company positions and strategies, and to characterize high and low growth technologies for competitors.

(2) New venture evaluation

Patent analysis can be used to evaluate potential technology acquisitions, and to analyze joint venture opportunities.

(3) Patent portfolio management

Patent analysis can be used to identify valuable patents, product areas, and potential technical customers.

(4) R&D management

Patent analysis can be used to analyze process or product plans, and to define pacing technologies.

(5) Product area surveillance

Patent analysis can be used to review new patent content and ownership, and to check for infringements.

Mogee (1991) suggested that patent analysis can be used in four areas including rival analysis, technology tracking and forecasting, identifying important technical development, and international strategic analysis. These applications are discussed as follows.

(1) Rival analysis

Using technology codes included in the patent records, it is possible to characterize the technological directions being pursued by individual firms.

(2) Technology tracking and forecasting

The technology trends and forecasts obtained for two very different technologies－one emerging and one mature－illustrate what may be learned from international patent data.

(3) Identifying important technical development

Firms often wish to identify the truly important technological development in a field, or they may want to know which inventors or firms have been doing the most influential technical work. It is thus desirable to be able to determine the importance of individual patents. The method of doing this is by weighting the patent counts with the number of citations received from later patents.

(4) International strategic analysis

Patent information can provide insight into a company's strategy for exploiting its technology internationally. One may infer from the fact that a firm has applied for a patent in a particular country that the firm sees potential economic value to be derived from making, using or selling the invention in that country. Hence, the international strategies of particular firms can be characterized by looking at the proportion of their inventions patented in various countries.

Liu & Shyu (1997) proposed that competitive analysis and technology trend analysis are mainly analytical areas for patent analysis.

(1) Competitive analysis

By rearranging the data in patents, such as an assignee, filed dates, granted dates, and IPC code, the following information is revealed:

a. The technology strength of a firm can be justified by the number of patents granted to specific technical fields.

b. The number of filed and granted patents can reflect the life cycle or growth periods of a specific technology.

c. Citation count of a patent illustrates its relative importance in designated technical fields.

d. R&D planning is undertaken by obtaining the technological information of competitors.

(2) Technology trend analysis

Technology development trend contrasts with a sigmoid or S curve. The relationship between patent counts and assignee numbers on an annual trend illustrates such a phenomenon (Figure 2.13). In the early stage in which a technology is introduced, very few patents are issued and a limited number of firms or assignees are in the area of interest. Once a technology reaches a fast-growing period, many patents are filed. After having reached a plateau, only few patents are granted and few firms still invest in the area.

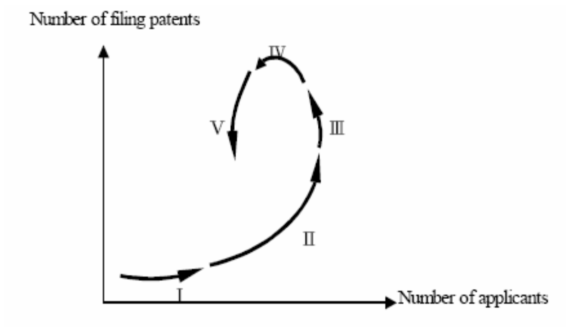


Figure 2.13 Patent statistics displaying the life cycle of a technology

Data source: Liu & Shyu (1997)

Ernst (2003) recommended the value of patent information for strategic planning, and built a conceptual framework showing the applications of patent analysis in technology management. Patent analysis can be employed in three areas as follows.

(1) Competitor monitoring and technology assessment

Patent analysis provides relevant information about the competitor's R&D strategies and helps to assess the competitive potential of technologies. Some important questions of technology management addressed in this context include: How can technological changes in the competitive environment of the firm be detected and evaluated? How can the firm's position be evaluated in comparison with the competition in technological fields? How can changes in the competition's technology strategies be identified? How can the R&D budget be allocated to the most promising technologies?

(2) Identification and assessment of sources for external technology creation

Patent analysis can be used to identify and assess options for the external generation of technological knowledge. Some important questions of technology management addressed in this context include: How can external technological know-how which is relevance to the firm be identified? How can the technological position of potential acquisitions and R&D alliance partners be evaluated? How can the technological fit between the acquisition target or the R&D alliance partner and one's own firm be determined?

(3) Human resource management in R&D and knowledge management

Patent analysis can be used for storing relevant knowledge as a core element of knowledge management and as a tool for human resource management in R&D. Some important questions of technology management addressed in this context include: How relevant knowledge can be made available to recipients in the organization? How can the leading inventors in a specific technological field be found? How is it possible to ensure that leading inventors remain in the acquired firm?

These above studies are concerned with various issues such as technology, R&D, product, investment and strategy. Lai et al (2006; 2006a) further integrated literatures of patent analysis and proposed a framework of taxonomy in terms of different levels of patent analysis. In the framework, patent analysis can be used at different levels of analyses such as country, industry, corporation and technology levels. Furthermore, each level contains several areas of applications. These levels and areas are illustrated as follows and shown in table 2.2.

(1) Country level

Patent analysis can be used to make technology policy (Jaffe, 2000; Furman et al., 2002) and make international comparison (Tong & Frame, 1994; Grupp & Schmoch, 1999).

(2) Industry level

Patent analysis can be used to evaluate technology knowledge spillovers (Scherer, 1982; Jaffe et al., 2000), analyze competitive market intelligence (Ashton & Sen, 1988; Ernst, 2003), and link the relationship between science and technology (Meyer, 2000; 2001; 2006a).

(3) Corporation level

Patent analysis can be used to judge corporate strategy (Breitzman & Mogee, 2002; Reitzig, 2004), develop technology plans (Ernst, 2003) and evaluate R&D investment plans. (Breitzman et al., 2002; Tsuji, 2002).

(4) Technology level

Patent analysis can be used to evaluate technological development (Basberg, 1987; Liu & Shyu, 1997; Huang et al., 2003) and manage the R&D process (Pavitt, 1985; Narin, 1995).

Table 2.2 Framework of taxonomy for patent analysis

Levels	Areas
Country	Technology policy; International comparison
Industry	Knowledge spillovers; competitive intelligence; Science and technology
Corporation	Corporate strategy; Technology plans; R&D investment plans
Technology	Technological development; R&D management

Data source: Lai et al. (2006; 2006a)

The aims of this study are to implement patent analyses to monitor the technological states and trends of CNT-FED and CNT fabrication. In other words, the trends of technological development are main research objectives in this study. Thus, the level of patent analysis in this study belongs to the technology level according to the framework.

2.3.3 Methods of patent analysis

In general, patent analysis employs various methods to analyze the bibliometric data in the patent documents. The valuable information is produced through these methods of analysis. Hence, the methods of analysis are important and useful tools in patent analysis. There are many methods in patent analysis such as patent counts, citation analysis, co-citation analysis, co-word analysis, coupling analysis, network analysis, and so on. This section classifies these methods into three types including patent indicators, patent classification, and patent maps, as well as discusses as follows.

(1) Patent indicators

Patent indicators are important base in patent analysis. These indicators can assist researchers in understanding critical technology information about company and competitors. Several studies proposed various patent indicators for different goals of patent analysis. Narin (1994) suggested seven patent citation indicators. Also, Karki (1997) introduced six technological indicators. These indicators are all based on patent citation analysis. Through eliminating the overlap, total of nine indicators are listed as Table 2.3. These indicators are helpful for understanding the technology profiles and the patent activities of companies.

Table 2.3 Patent indicators suggested by Narin & Karki

Patent indicator	Definition
Number of patents	Number of granted patents of a company in a particular period
Patent growth rate	Comparing the number of granted patents in this year with the number of granted patents in last year
Highly cited patents	Frequently cited patents in the subject field
Technical impact index	Percent of patents in a particular period which are in the most highly cited 10% of all patents
Technology cycle time	Median age of the earlier US patents reference cited in the company's new patents
Current impact index	How often patents are cited in other patents
Technology strength	Number of patents multiplied by the current impact index
Science linkage	Number of other publications cited in a patent
Science strength	Number of patents multiplied by the science linkage

Data source: Narin (1994) & Karki (1997)

Moreover, Ernst (1998; 2003) proposed some patent indicators to assist companies in competitor monitoring, technology assessment, R&D management, and the identification and assessment of potential sources for the external generation of technological knowledge. These indicators are listed as Table 2.4.

Table 2.4 Patent indicators suggested by Ernst

Patent indicator	Definition
Patent activity (PA_{iF})	Patent applications (PA) of firm *i* in technological field (TF) *F*
Technology share (based on patent application)	PA_{iF} / PA of all competitors in TF *F*
R&D emphasis	PA_{iF} / Number of firm's (*i*) total patent applications
Co-operation intensity	Number of joint patent applications with partners in TF *F* / PA_{iF}
Share of granted patents (Q_1)	Granted patents of firm *i* in TF *F* / PA_{iF}
Technological scope (Q_2)	Diversity and number of IPC classes in firm *i's* patent applications
International scope (Q_3)	Size of patent family and share of triad (US, JP and EPO) patents of PA_{iF}
Citation frequency (Q_4)	Average citation frequency of PA_{iF}
Average patent quality (PQ_{iF})	Sum of all indicators of patent quality ($Q_1 - Q_4$)
Patent strength (PS_{iF})	Product of average patent quality (PQ_{iF}) and patent activity (PA_{iF})
Technology share (based on patent strength)	PS_{iF} / PS of all competitors in TF *F*
Relative technology share	PS_{iF} / Maximum patent strength of a firm in TF *F*
Share of valid patents	Valid patents / Granted patents of firm *i* in TF *F*
Share of US patents	US patents of firm *i* in TF *F* / PA_{iF}
Citation ratio	Patent citations of firm *i* in TF *F* / PA_{iF}

Data source: Ernst (1998; 2003)

(2) Patent classification

The classification of patents is to sort all patents within a patent dataset into several groups. The patents in each group have a high degree of similarity or homogenous, and each group is heterogeneously discriminated from the other groups. The purpose of classification is to manage technology packages or monitor patent portfolios. In general, the current studies most apply the International Patent Classification (IPC) or the United States Patent Classification (UPC) to identify patents. Furthermore, Lai & Wu (2005) proposed a new patent classification system, which is called the patent co-citation approach (PCA), to the needs of a specific industry for patent management. On the other hand, patent coupling approach, which is based on the bibliographic coupling method, is another new patent classification. And, co-word method, which counts the co-occurrence of keywords within the documents, is the unique tool for classification. In addition, cluster analysis and multidimensional scaling (MDS) are also used to classify a set of patents into different groups. These methods are discussed as follows.

a. International Patent Classification

According to the definition of World Intellectual Property Organization (WIPO), International Patent Classification (IPC) is an internationally uniform classification of patent documents. The aim of IPC is the establishment of an effective search tool for the retrieval of patent documents. The IPC is a hierarchical classification system comprising section, classes, subclasses, main groups, and subgroups. The classification contains the whole knowledge which may be regarded as proper to the field of patents for invention.

b. United States Patent Classification

According to US Patent and Trademark Office (USPTO), United States Patent

Classification (UPC) is a code which provides a tool for classify the invention. It contains the class and subclass. There are about 450 classes of invention and about 150,000 subclasses of invention in the UPC.

c. Patent co-citation approach

Lai & Wu (2005) used the co-citation analysis to propose a classification approach called the patent co-citation approach (PCA). The co-citation is an approach to evaluate the similarity of documents. It is defined as the frequency with which two documents are cited together (Small, 1973). The PCA is a methodology based on co-citation for creating a patent classification system by classifying industry basic patents. After the patent classification system is built, the target patents will be classified by being compared with the basic patents. The target patents are patents to be classified and basic patents are patents repeatedly cited by target patents. The PCA is more suitable for patent-crowded industries, such as the semiconductor industry and the electronics industry.

d. Patent coupling approach

In addition to co-citation, patent coupling is another approach to assess the similarity of patents. The concept of patent coupling is transferred from the bibliographic coupling method, which was proposed by Kessler (1963), onto patent analysis. Comparing with PCA, citing patents are the subject of analysis in patent coupling approach, while the focus of PCA is on the cited patents. Lo (2008) applied the concept of patent coupling approach to identify seven technological clusters in genetic engineering research.

e. Patent co-word method

The patent co-word method is another tool to cluster a set of patents into several groups. The foundation of co-word method is the idea that the co-occurrence of keywords describes the contents of the documents (Callon et al., 1991). Two keywords co-occurring within the same document are an indication of a link between the topics to which they refer. Hence, the co-word occurs in the patent documents can be used to the base of patent classification. Several studies employed patent co-word method to identify the clusters. For instance, Noyons & Van Raan (1994) and Engelsman & Van Raan (1994) both used patent co-word method to develop the cartography of technology and identify several clusters in the particular fields of technologies. In addition, Penan (1996) employed patent co-word method to describe 11 R&D strategy clusters in the field of Alzheimer's disease therapy.

f. Multidimensional scaling

Multidimensional scaling (MDS) is a common statistical method for classification. MDS technique can be employed to classify patent data. For instance, Lai & Wu (2004) analyzed patent data to find five technology strategy groups by using MDS technique in Taiwan semiconductor industry.

g. Cluster analysis

Cluster analysis is another general statistical method to classification. It can be used to sort all patents within a patent dataset into several clusters. For instance, Chang et al (2006) used cluster analysis to classify 98 samples of patent portfolios of 37 companies into five technology groups.

(3) Patent maps

The visualization methods for patent analysis are called the patent maps. A patent map is the visual expression of total patent analysis results to understand complex patent information easily and effectively (Kim et al., 2007). Moreover, it is useful as reasonable mirror for the analysis of important processes in the technological endeavor. There are several important advantages in using the patent maps. First, a visualization of complex masses of data offers a more complete overview in less time. Second, visual information is more easily remembered. Third, the reduction of information is also an important point. It is a crucial problem to filter the significant features. Finally, the maps can be seen as tools for searching, identifying and analyzing the structure of technological activities as reflected by patents.

In general, patent maps can be generated by various bases of methods such as citations, co-citation, co-word, patent coupling, and so forth. This study divided these methods into two kinds of maps including citation-based maps and word-based maps.

a. Citation-based maps

Patent citation analysis, which is a quantitative tool to search for the relations between citing and cited patents, is an important base to generate maps or networks. The citation-based maps are useful to mapping the technological trajectories in the field of technology being studied. Many studies used different kinds of patent citations to construct patent maps or networks, such as citation flow networks (Verspagen, 2000; 2007; Li et al., 2007), co-citation maps (Chen & Hicks, 2004; Wartburg et al., 2005), and patent coupling maps (Huang et al., 2003; Kuusi & Meyer, 2007; Lo, 2008).

b. Word-based maps

The word-based maps use the important words in the patent documents as the input base to produce patent maps. Due to these words are generated from the patent documents themselves, the maps are capable of detecting the internal structure of a set of patents. The co-word method and keyword method are main bases for producing the patent maps. Co-word method consists in constructing a matrix of adjacency for the co-occurrence of words in the patent documents. Several studies used co-word methods to construct the patent maps, which is called the co-word map (Noyons & Van Raan, 1994; Engelsman & Van Raan, 1994; Penan, 1996; Tseng et al., 2007). On the other hand, Yoon & Park (2004) employed the frequency of keywords occurrence in patent documents as the input base to generate a visual maps, which is called the patent network.

On the basis of above mention, patent indicators, patent classification, and patent maps are three main types of methods for patent analysis. Although each type represents different focus of analysis, the three types are not independence. These types of methods can be interchangeably combined for patent analysis. For instance, patent maps not only display the overview of patents, but also sort these patents into several clusters or sub-maps (Noyons & Van Raan, 1994; Engelsman & Van Raan, 1994; Penan, 1996). As well, several indicators could be used to identify the characteristics of maps or clusters (Verspagen, 2000; Yoon & Park, 2004; Lo, 2008). Thus, the relationship among the indicators, classification and maps are hierarchic.

Figure 2.14 shows a framework regarding the levels of types for patent analysis. The patent indicators are the foundational level in the framework. The researchers can calculate different indicators to get the pieces of knowledge. The patent classification is the middle level. The application of patent classification analysis can include the use of patent indicators. The researchers can detect the characteristics of clusters through computing relevant indicators. The patent map, which can contain the other two types, is the highest level in the framework. The researchers can visually comprehend the overview of map and classify the map into different clusters or sub-maps. The indicators can be further used to identify the characteristics of maps and clusters.

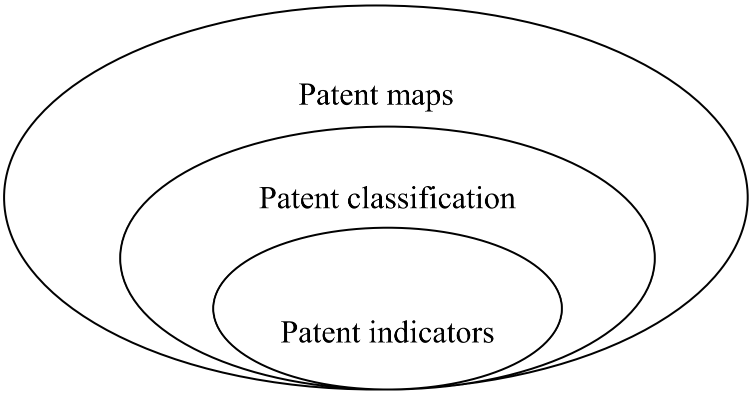


Figure 2.14 The levels of types for patent analysis

This study uses patent bibliometric analysis and patent network analysis to analyze the technological states and trends of CNT-FED and CNT fabrication. The two methods contain all of three types of patent analysis. In patent bibiometric analysis, several indicators can be used to analyze different aspects of patent activities. In patent network analysis, the overall network can visually display the relationship among all patents. Cluster analysis can be used to classify all patents within the patent network into several clusters. Furthermore, the characteristics of network and clusters can be identified through calculating the relevant indicators. In the next sections, the two methods which used in this study would be introduced in detail.

2.4 Patent bibliometric analysis

Bibliometrics is a quantitative analysis done to aid the evaluation of research performance (Van Den Berghe et al., 1998). Patent bibliometric analysis is a research method utilizing bibliometrics to perform patent information analysis in order to evaluate technological activities (Narin, 1994). The opinion of using bibliometrics for analyzing patent information could be dated back to 1940s when Arthur H. Seidel proposed producing a citation index of the patent literatures and Harry C. Hart endorsed the idea in a later issue (Garfield, 1979). Although the opinion turned up at that time, nothing was done of their suggestions. It was till 1964 when the first citation index to the patent literatures was published. Even though the opinion of building citation index for patent information was mentioned in 1940s, however, neither patent citation nor other bibliometrics was broadly applied for patent literature analysis until last decade (Lo, 2007).

Narin (1994) applied the bibliometrics to establish the use of patent bibliometric analysis. Since then several studies had been conducted by taking the patent bibliometric analysis. The bibliometric data in the patent documents include information as follows (Gupta & Pangannaya, 2000):

(1) Patent number
(2) Application number
(3) Date of issue
(4) Date of application
(5) Title
(6) Country
(7) Inventor
(8) Assignee
(9) Kind of document
(10) International patent classification
(11) References
(12) priority

Researcher can utilize various methods and techniques to analyze the data and find the developmental states of the patented technology. In general, statistical analysis and citation analysis are the main research methods for patent bibliometric analysis. Statistical analysis performs statistical calculations on the chosen set of bibliometric data to analyze the development and distribution of the patented technology. For statistical analysis, patent counting is the most common method used. By counting the number of patents granted each year, the growth of the patents could be analyzed (Gupta & Pangannaya, 2000). Moreover, the method was also applied to analyze the productivity on countries, assignees and inventors (Narin, 1994; 1995; Karki, 1997; Banejee et al., 2000; Gupta & Pangannaya, 2000). On the other hand, other patents and non-patent literatures cited in the patent documents are main analytical focal points of citation analysis. Determining the most highly cited patents reveals the important patents in the field and establishes the technological foundation of the patents being studied. The analysis of non-patent literature cited in the patent documents can uncover the linkages between the patented technology and basic science and ascertain the scientific foundation of the relevant patents (Karki, 1997).

According to above mention, patent bibliometric analysis is suited to evaluating technological activities including the status, relationship, technological and scientific foundation of the patents being studied. Thus, this study uses patent bibliometric analysis to uncover the developmental path and current states of CNT-FED technology and CNT fabrication.

2.5 Patent network analysis

Network analysis, by emphasizing the relationship connecting the social positions within a system, offers a powerful brush for painting a systematic picture of global social structures and their components (Knoke & Kuklinski, 1982). Network analysis attempts to describe the structure of interactions (edges) between actors (nodes). Actors are the given entities in the network. The relationship among actors and the location of individual actors in the network provide rich information and assist the researcher in comprehending the overall structure of the network. Furthermore, network analysis utilizes quantitative techniques to generate relevant indexes, which clarify the characteristics of the whole network and show the position of individuals or groups in the network structure (Wasserman & Faust, 1994).

Although network analysis was developed mainly for sociological studies, it is utilized widely in other research areas (Leoncini et al., 1996; Cross et al., 2001; Chang & Shih, 2005; Calero et al., 2006; Shin et al., 2006). Particularly, several studies used network analysis in bibliometric contexts such as following subjects. Van Raan & Petters (1989) used a co-subfield approach, which is based on assignment of cross-sections, to construct networks which successive periods of time. The subfield-network structure can be used to monitor the dynamical process in the development of chemical engineering. Courtial & Callon (1991) employed co-word method to construct networks and to specify essential research themes in the field of polymer science and technology. They not only illustrated that these themes often follow characteristic cycles, but also suggested that it is possible to evaluate the relevance of funding support. Van Raan & Tijssen (1993) drew the bibliometric maps for the area of neural network research by using the co-word method. These maps can reveal overall relationship and important features, and the bibliometric mapping has the epistemological values. Finally, Verspagen (2007) implement patent citation networks to map technological trajectories in the field of fuel cells. The goals of his study are to discover the main path and the life cycle in the development of the field.

Even though all of these studies construct networks (or maps) of particular field, they used different methods such as co-subfield, co-word and patent citation. Co-subfield method is useful to understand synthesis of knowledge from different subfields of science. It can show any potential insight into the disciplinary structure of science. Co-word method consists of constructing a matrix of adjacency for the co-occurrence of words in scientific texts. The advantage of co-word method is that words are the foremost carrier of scientific concepts, and their use is unavoidable and they cover an unlimited intellectual domain (Van Raan & Tijssen, 1993). On the other hand, patent citation method demonstrates the linkage of causal relationship between citing and cited patents. It is suited to tracing the historical development of the main path in the subject field. In addition, Trajtenberg (1990) further verified the value of patent citations. He suggested that patent citations represent indicators of the value of innovations by showing that there is a close relationship between patent counts weighted by citations and the social value of innovations in the Computer Tomography scanners.

Recently, Yoon & Park (2004) used the concept of network analysis in patent analysis, and suggested patent network analysis. This method uses the frequency of keywords occurrence in patent documents as the input base to produce a visual patent network. The relations among patents represent edges in the patent network while individual patents represent nodes. Patent network analysis can visually display all the relationship among the patents and assists the researchers in intuitively understanding the entire structure of the patent database. In addition, because network analysis uses several patent keywords as its input, this method is capable of detecting the internal structure of patent network and thereby produces useful results. Comparing with co-subfield, co-word and patent citation method, this method is close to co-word method. This method and co-word method both use keywords as the input base of analysis, but there is still difference between them. The major difference is that this method calculates the frequency of keywords occurrence in each document, while co-word method analyzes how many times that keywords occurs together (co-occurrence) with any other keyword in documents involved.

Patent network analysis uses two mathematical tools to present the information from the patent network, namely graphs and quantitative techniques. Graphs can visually display the structure of a set of patents by generating a patent network. However, if too many patents are involved or a wide variety of patent relationship exits, graphs will become too complicated to show the exact relationship among the patents. In that case, the indexes calculated from quantitative techniques can clearly show the information on the patent network. The detailed methods of the two mathematical tools would be described in the section of methodologies.

There are several advantages in the patent network analysis. First, the visualized display of the network enables the researchers to easily understand the global structure of the patent set in that it shows both the overall relations among patents and the respective positions of individual patents in the network. Second, network analysis enriches the potential utility of patent analysis because it takes more diverse keywords into account and produces more meaningful indicators. Third, it assists the researchers in determining the relative importance of individual patents. The analysis generates a selective set of influential patents that deserve more intensive control. Finally, it facilitates analysis of up-to-date trend of high technologies and identification of promising avenues for new product development (Yoon & Park, 2004). Due to the advantages as above mention, this study uses patent network analysis which including graphs and quantitative techniques in order to monitor the technological trends in the fields of CNT-FED and CNT fabrication.

Chapter 3 Methodologies

3.1 Data selection

3.1.1 Patents of CNT-FED

The data of patent documents in the field of CNT-FED were obtained from the U.S. Patent and Trademark Office (USPTO) database available at www.uspto.gov, and all these selected patents belong to the granted patents. The search was made by looking for the following codes in the titles and abstracts of patent documents: "carbon nanotube and field emission display", "carbon nanotube and field emission displays", "carbon nanotubes and field emission display", "carbon nanotubes and field emission displays", "carbon nano tube and field emission display", "carbon nano tube and field emission displays", "carbon nano tubes and field emission display", "carbon nano tubes and field emission displays", "carbon nano-tube and field emission display", "carbon nano-tube and field emission displays", "carbon nano-tubes and field emission display", "carbon nano-tubes and field emission displays" and "CNT-FED". The experts in the area of CNT-FED then reviewed the search results and eliminated the irrelevant ones. 98 patents from 1996 to 2007 were collected. The subject set contains patents from U.S. Patent No. 5,531,880 to U.S. Patent No. 7,176,614. However, because the patent numbers are too long to be usable for patent analysis, the patents were sorted by issue date and labeled with serial numbers from 1 to 98, with number one being the oldest patent.

3.1.2 Patents of CNT fabrication

The data of patent documents in the field of CNT fabrication were obtained from the U.S. Patent and Trademark Office (USPTO) database available at www.uspto.gov, and all these selected patents belong to the granted patents. The search was made by looking for the code "carbon nanotube" or "CNT" in the titles and abstracts of patent documents. The experts in the area of CNT then reviewed the search results and eliminated the irrelevant ones. 92 patents from 2000 to 2007 were collected. The subject set contains patents from U.S. Patent No. 6,062,931 to U.S. Patent No. 7,235,159. However, because the patent numbers are too long to be usable for patent analysis, the patents were sorted by issue date and labeled with serial numbers from 1 to 92, with number one being the oldest patent.

3.2 Patent bibliometric analysis method

Patent bibliometric analysis is a research method utilizing bibliometrics to perform patent information analysis in order to evaluate technological activities (Narin, 1994). Bibliometric data such as patent number, document type, issue date, country, title, inventor, assignee, international patent classification, application date, and so forth in patent documents are analyzed (Gupta & Pangannaya, 2000). Researcher can utilize various techniques, such as statistical analysis and citation analysis, to analyze the bibliometric data in the patent documents as well as to find the developmental path and current states of the patented technology.

This study uses patent bibliometric analysis to analyze 98 CNT-FED patents and 92 CNT fabrication patents to uncover the developmental path and current states of CNT-FED technology and CNT fabrication respectively. First, we use statistical analysis to find the growth in patents and perform country comparison, assignee comparison, and inventor comparison. Then, we use citation analysis to analyze highly cited journals to quantify the dependence of technology on basic science, and to analyze highly cited patents to find out the important patents in the fields of CNT-FED and CNT fabrication.

3.3 Patent network analysis method

After patent bibliometric analysis, the next step for this study is to use patent network analysis to examine the overall relationship of CNT-FED and CNT fabrication patents respectively as well as to find out the key patents. Patent network analysis uses two mathematical tools to present the information from the patent network, namely graphs and quantitative techniques. Graphs can visually display the structure of a set of patents by generating a patent network. However, if too many patents are involved or a wide variety of patent relationship exits, graphs will become too complicated to show the exact relationship among the patents. In that case, the indexes calculated from quantitative techniques can clearly show the information on the patent network. This study uses both graphs and quantitative techniques to examine thoroughly the structure of the patent network.

For graphing the patent network, this study adopts the following steps proposed by Yoon & Park (2004):

Step 1: Technical experts select the relevant patent keywords based on the substance and characteristics of the patented technologies.

Step 2: Calculating the frequency of keywords occurrence in patent documents and integrate the data into keyword vectors. The keyword vectors from patent 1 to patent *m* are as follows:

$$\begin{array}{ll} \text{Patent 1:} & (k_{11}, k_{12}, k_{13}, \cdots, k_{1n}) \\ \text{Patent 2:} & (k_{21}, k_{22}, k_{23}, \cdots, k_{2n}) \\ \vdots & \vdots \\ \text{Patent } m\text{:} & (k_{m1}, k_{m2}, k_{m3}, \cdots, k_{mn}) \end{array} \quad (1)$$

For example, in the document of patent 1, the first keyword occur k_{11} times, the second keyword occur k_{12} times and so on as above.

Step 3: Utilizing Euclidian distance to calculate the distance between the patents and to establish the relationship among patents. If keyword vectors of patent *i* and patent *j* are defined as $(k_{i1}, k_{i2}, \cdots, k_{in})$ and $(k_{j1}, k_{j2}, \cdots, k_{jn})$ respectively, the Euclidian distance value (E_{ij}^{d}) between the two vectors is computed as follows:

$$E_{ij}^{d} = \sqrt{(k_{i1} - k_{j1})^2 + (k_{i2} - k_{j2})^2 + \cdots + (k_{in} - k_{jn})^2} \tag{2}$$

Step 4: Euclidian distance matrix (E^{d} matrix) is composed of all Euclidian distance values among all vectors. However, the E^{d} matrix must be dichotomized in order to graph the patent network. It is necessary to transform the real values of E^{d} matrix into standardized values from 0 to 1 for dichotomizing in the next step.

$$E_{ij}^{s} = \frac{E_{ij}^{d}}{Max(E_{ij}^{d}, i = 1, \cdots, m; j = 1, \cdots, m)} \tag{3}$$

The E^{s} matrix is interpreted as dividing the all values of E^{d} matrix by the maximum value of E^{d} matrix. The all values of E^{s} matrix are from 0 to 1.

Step 5: The cell of the E^{s} matrix must be a binary transformation, comprising 0s and 1s if it is to exceed the cut-off value *p*:

$$I_{ij} = \begin{cases} 1, & \text{if } E_{ij}^{s} < p \\ 0, & \text{if } E_{ij}^{s} \geq p \end{cases} \tag{4}$$

The *I* matrix includes binary value where I_{ij} equals 1 if patent *i* is strongly connected with patent *j*. I_{ij} equals 0 if patent *i* is weakly connected with patent *j* or not at all connected. That is, if the E_{ij}^{s} value is smaller than the cut-off value p, the connectivity between patent i and patent j is regarded as strong and the I_{ij} value is set to 1. Otherwise, the connectivity is considered weak and the I_{ij} value is set to 0. The determination of cut-off value is a task of trial-and-error. The researcher has to select a reasonable cut-off value so that the structure of the network becomes clearly visible. Then, the I matrix can be employed to develop a patent network.

This study examines the relationship of patents using network analysis at the overall network and cluster levels. At the overall network level, this study uses the whole patent network to examine the overall relationship and to find the key patents. At the cluster level, this study clusters patents with similar technologies together to form a technology package. By examining the detailed relationship among the patents in each cluster, the characteristics of the clusters and important technologies are identified.

In quantitative techniques, several indexes can be employed to examine the structure of the patent network at the overall network and/or cluster levels. The first index that finds out the relatively important patents at overall network and cluster levels is technology centrality index (TCI):

$$TCI_i = \frac{C_i}{n-1} \tag{5}$$

$C_i = \sum r$, r: ties of patent i

where n denotes the number of patents. The technology centrality index of a patent network is interpreted as the ratio of the number of tied links to all n-1 other patents. It measures the relative importance of a subject patent by calculating the density of its linkage with other patents (Yoon & Park, 2004). That is, the higher the centrality index, the greater the impact on other patents. The technology centrality index can be used to identify the influential patents in the field of the technology being studied. Moreover, detailed information on these influential patents needs to be obtained. Technological and strategic implication can be deduced from the information as well.

Furthermore, in order to comprehend the trends of technological progress, it is important to monitor the life cycle of subject technology. Technology cycle time (TCT) index can be used to measure the technological progress by gauging the degree of newness of patents at the overall network. Let T_i be the application date of patent *i*, and the formula for calculating TCT index of patent *i* is shown below:

$$TCT_i = \underset{j}{Median}\left\{ \left| T_i - T_j \right| \right\} \tag{6}$$

where patent *j* and patent *i* are connected. It is defined as the median value of the age gaps between the subject patent and other connected patents (Yoon & Park, 2004). Shorter cycle time reflects faster technology progress; longer cycle time reflects slower technology progress. Thus, patents relating to a rapidly progressing technology should have a smaller technology cycle time index than patents relating to a slowly progressing technology. The changing trends of technological advancement should be carefully monitored in technology management.

Finally, density index (DI) can be used to make a comparison among clusters and to realize the characteristic of connection in the network of each cluster. It is a proportion that defined as the number of ties present in the network of cluster divided by the maximum possible number of ties present in the network of cluster (Wasserman & Faust, 1994):

$$DI = \frac{T_c}{n_c(n_c - 1)} \tag{7}$$

where T_c denotes the number of ties present in the network of cluster, and n_c denotes the number of patents in the network of cluster. The density index measures the internal cohesion in the network of each cluster. That is, the higher the density of the cluster, the more connected technology package, and vice versa.

Chapter 4 Results of analyses: Carbon nanotube field emission display

4.1 Results of patent bibliometric analysis

This study uses bibliometric techniques to analyze the status of technological development in the field of CNT-FED. Looking at different aspects of patenting activities such as the growth in patents, country comparison, assignee comparison, inventor comparison, highly cited journals, and highly cited patents; the goal is to understand the developmental path and current states of CNT-FED technology.

4.1.1 Growth in patents

Table 4.1 demonstrates the growth in the number of patents for the field of CNT-FED. Although the first patent was issued in 1996, there was no obvious increasing in numbers of patents between 1996 and 2000. Nevertheless, the notable fact is that patenting activity is much active from 2002 to 2006, and the majority of above patents are filed from 2000 to 2003. Generally speaking, it takes about one to three years in moving patent application to patent issue. Therefore, based on either dates of issue or application, it is clear that CNT-FED technology developed significantly after 2000, and the patent application is rapidly increased. This is confirmed by the truth that the CNT-FED manufacturers in South Korea, Japan and Taiwan released successful proto-type CNT-FED products starting in year 2000. However, after 2004, the number of patent application obviously slowed down. Even though the published applications in 2005 and 2006 were included in this analysis, the trend of patent growth just increases a little bit. The legal change for US patent system in the year of 2001 seems to have slight influence, but it doesn't change the whole trend of the patent growth between 1996 and 2006. The reason for the slow down may be that the technology in the field was in its nascent stage, a lot more basic science issues needed to be understood and technological bottlenecks needed to be overcome before any further progress on the technological development process could take place. Nowadays, the main bottlenecks of CNT-FED in technology field are due to the growth process of CNT and the design of electronic circuit for emitter. If these troubles are solved, the growth can be expected for the patents and marketable products.

Table 4.1 Growth in patents for CNT-FED

Application date		Issue date	
Year	Number of patents	Year	Number of patents
1994	1	—	—
1995	2	—	—
1996	4	1996	1
1997	2	1997	3
1998	6	1998	4
1999	9	1999	1
2000	15	2000	6
2001	16	2001	2
2002	19	2002	14
2003	15	2003	12
2004	8	2004	20
2005	1	2005	14
—	—	2006	18
—	—	2007	3
Total	98	Total	98

4.1.2 Country comparison

Table 4.2 provides information on the distribution of patenting activity in different countries. South Korea and USA are the most active in patents for the field of CNT-FED. Taiwan comes next and is followed by Japan. This means that the four major countries for CNT-FED development are South Korea, USA, Taiwan and Japan. In addition, it is noteworthy that China filed four patents and all were issued in 2006 and 2007. Although the number of patents filed is small, it still shows that China is starting to pay attention to this domain. This situation also indicates that their government attaches great importance to science and technology, nano-materials and their related products especially.

Table 4.2 Country comparison in the field of CNT-FED

Patent application country	Number of patents
South Korea	38
USA	31
Taiwan	20
Japan	9
China	4
Others	5
Total number of all patents of all countries	107
Total number of all patents	98

Note: There is discrepancy between "total number of all patents of all countries" and "total number of all patents" because 9 patents were filed by two countries at the same time.

4.1.3 Assignee comparison

Because one of the reasons for seeking patent protection is to show an interest in the commercial exploitation of a new technology, most of the patent assignees are industrial enterprises (Schmoch, 1997). The field of CNT-FED is no different. Table 4.3 shows the patenting activity of assignees ranging from corporations, R&D institutes, consortiums of corporations and academia, and consortiums of corporations and individuals. The data indicate that corporations owned 71 patents, 72% of the total patents in the field.

This study goes further to analyze each assignee and attempts to find out which assignees are the most active in CNT-FED development. Among corporate assignees, Samsung from South Korea is the leading corporation with the highest number of patents in the field. This confirms the fact that South Korean corporations are the technological leaders in CNT-FED. The second most active corporations are Micron Technology and Motorola from USA and

Sony from Japan. Among all R&D institutes, Industrial Technology Research Institute (ITRI) from Taiwan is the most active in patents in this field. The second most active R&D institute, Electronics and Telecommunications Research Institute from South Korea, lags far behind and owned only 4 patents. Furthermore, ITRI owned the majority of patents filed in Taiwan. It can be seen that the R&D of CNT-FED technology in Taiwan clusters on research institutes. Taiwanese research institutes do the R&D first and then transfer the technology in the field of CNT-FED. There are 5 patents from consortiums of corporations and academia. Four of which were filed jointly by Hon Hai Precision Company in Taiwan and Tsinghua University in China. This shows that there is close cooperation between manufacturers in Taiwan and academic institutions in China. Only one patent, which was filed by Samsung and inventor Young-hee Lee, is from a consortium of corporation and individual.

Table 4.3 Assignee comparison in the field of CNT-FED

Assignee	Number of patents
Corporations	71
R&D institutes	21
Consortiums of corporations and academia	5
Consortiums of corporations and individuals	1
Total	98

4.1.4 Inventor comparison

A patent application includes the names of all contributors and researchers as co-inventors who directly contributed to the patentable features of the invention (Gupta & Pangannaya, 2000). Table 4.4 indicates the pattern of co-inventorship in the field of CNT-FED. Only 15 patents of 98 are from single inventors, all the remaining patents are from co-inventors. More than half of all patents are from two or three inventors. The remaining patents come from four or more inventors. The highest number of inventors for one patent is 7. It is clear that research in CNT-FED technology development is most frequently done by

R&D teams.

Table 4.4 The pattern of co-inventorship in the field of CNT-FED

Number of inventors in each patent document	Number of patents
1	15
2	26
3	25
4	16
5	10
6	2
7	4
Total	98

The data of inventors could be further analyzed to find out the total number of patents owned by each inventor. In other words, it can evaluate the productivity of inventors in the patents of CNT-FED. Table 4.5 shows the data of productivity of inventors. One inventor produced a maximum number of eight patents, and the most productive inventor is Jong-min Kim from Samsung in South Korea. The second most productive inventor is Cheng-Chung Lee from ITRI in Taiwan, who produced seven patents. However, 136 inventors produced only one patent each. The inventors owning only one patent make up 71.96% of all inventors. It means that few inventors owned more than one patent. The productivity of inventors is concentrated on a few inventors.

Table 4.5 Productivity of individual inventors in the field of CNT-FED

Number of patents owned by each inventor	Number of inventors
8	1
7	1
6	4
5	2
4	5
3	11
2	29
1	136

4.1.5 Highly cited journals

The literature cited in a patent may be used to quantify the dependence of a technology on basic science research (Narin & Olivastro, 1988). The non-patent literature (NPL) includes journals, books, meetings and so forth. NPL shows the linkages between science and technology. Karki (1997) proposed to use citations of NPL as indicators for studying the degree of linkage between patents and scientific literature. In other words, we can identify the scientific foundation of subject patents through citations of NPL.

For identifying the basic science knowledge underlying CNT-FED, this study examines the types and counts of journals that were cited in the CNT-FED patents. Table 4.6 shows some highly cited journals listed as sources of scientific information for patentable inventions in the field of CNT-FED. According to the Vinkler (1994) definition, the index of journal references concentration as the percentage share of journals containing 50% of total paper referred to. In this study, 50% of the references are covered by two journals, namely, Applied Physics Letters and Science. These two journals represent 6.6% of the total 30 journals. In contrast, the concentration of the referenced items in carbon nanotube patents was 12.5% of the total journals (Gupta & Pangannaya, 2000). Thus, they are strong contributor of basic scientific knowledge in the field of CNT-FED. Applied Physics Letters is a weekly journal featuring concise, up-to-date reports on significant new findings in applied physics. The letters emphasize rapid dissemination of key data and new physical insights. It can be seen that most basic knowledge of CNT-FED comes from the latest scientific concepts. Science is the leading journal of original scientific research in the world and publishes research in various scientific areas, including research on nanotechnology. The remaining highly cited journals are mostly from fields of applied physics as well as fields of applied chemistry. So it is evident that the basic scientific knowledge of CNT-FED comes mainly from applied physics and applied chemistry. This phenomenon also illustrates the new invention of

CNT-FED in journals can assist the researchers in designing a novel CNT-FED.

Table 4.6 Highly cited journals in the field of CNT-FED

Name of the journal	Number of citations
Applied Physics Letters	47
Science	40
Journal of Applied Physics	18
Nature	9
Journal of Vacuum Science & Technology	7
Chemical Physics Letters	6
Others	46
Total number of journals (30)	173

4.1.6 Highly cited patents

Karki (1997) points out that the highly cited patents are patents more than average technological impact. In other words, the higher the frequency of a patent's citations in subsequent patents, the more important is the cited patent. Table 4.7 shows the information on five highly cited patents among all mutually cited patents in the field of CNT-FED, including patent number 9, 6, 20, 17 and 15. These five patents provided important guidance in the early developmental phase of CNT-FED, and all of them are filed before 1999. These patents all deal with construction or composition for the electron emitter of FED and are considered the foundational patents for the technology. The front two patents are especially related to electron field emission devices and vacuum microelectronic device including an electrode comprising a layer having a dense array of microstructures as electron emitters. Others are related to a FED device that utilizes nanotube emitters instead of microtips as the electron emission source by thick film technique.

However, note that the serial numbers of the patents are sorted by the issue date. These five patents have early issue dates. Citation analysis is age dependent, therefore older patents have more chances of getting cited (Yoon & Park, 2004). Although citation analysis links the relationship of patents, it merely indicates individual links between citing and cited patents. The highly cited patents revealed by citation analysis represent only the important basic technology in the early period. Citation analysis cannot provide information on the overall relationship among all patents and reveal the most important patents in the field of the technology being studied. Therefore, it is necessary to examine the overall relationship among all patents in order to grasp the technological trends in CNT-FED.

Table 4.7 Highly cited patents in the field of CNT-FED

Patent number (Real number)	Cited frequency
9 (U.S. Patent No.5,973,444)	10
6 (U.S. Patent No.5,726,524)	10
20 (U.S. Patent No.6,359,383)	9
17 (U.S. Patent No.6,250,984)	9
15 (U.S. Patent No.6,146,230)	8

4.2 Results of patent network analysis

In the section, this study uses patent network analysis to further analyze the overall structures among the patents in the field of CNT-FED. First, we ask research fellows at the Nanotechnology Research Center at Feng Chia University to select keywords from CNT-FED patent documents. These research fellows all have many years of experience in CNT-FED research. Based on their screening, there are a total of 13 keywords, including “field emission display or FED”, “carbon nanotube or CNT”, “cathode”, “anode”, “phosphor”, “emitter”, “glass”, “vacuum”, “channel”, “gate”, “operating voltage”, “thick film printing” and “chemical vapor deposition or CVD”. Second, we count the frequency of keywords occurrence in each patent document. Since each patent document varies in length, it is not useful to compare the frequency of keywords occurrence because those numbers would be influenced by the number of total pages in each patent document. Therefore, this study divided the frequency of keywords occurrence by the number of pages in each patent document and integrated the results into keyword vectors for further analysis. Third, to connect the relationship between patents, Euclidian distance should be used to calculate the distance between keyword vectors. All Euclidian distance values among the vectors make up Euclidian distance matrix, E^d. And then, we transform E^d matrix into E^s matrix for dichotomizing in the next step. The all values of E^s matrix are from 0 to 1. Finally, the cut-off value, *p*, must be selected to dichotomize the cells of E^s matrix for graphing the patent network. The appropriate cut-off value is necessary to make the structure of the network become clearly visible (Yoon & Park, 2004). Through trying out numerous cut-off values, p = 0.27 was chosen, which indicates that I_{ij} equals 1 if E^s_{ij} is smaller than 0.27, otherwise I_{ij} equals 0. Consequently, the binary matrix, *I*, was built for the implementation of the network analysis. The patent networks were drawn by using UCINET 6.0 (Borgatti et al., 1999). In the following section, we describe the structural features of the patent networks at the overall network and cluster levels.

4.2.1 Overall network level

A well-constructed visual display of a network often conveys an intuitive knowledge of a system's structure (Knoke & Kuklinski, 1982). A preliminary visual structure of the overall patent network can be captured by using the graphing approach. Figure 4.1 shows the overall patent network in terms of connectivity. The network analysis divides all the patents into two sets, an interconnected set and an isolated set. The interconnected set represents the overall patent network, including 91 patents and the relationship among these patents. It provides much information for in-depth analysis. There are seven patents in the isolated set, including patent number 16, 44, 57, 63, 80, 81 and 85. Among these patent documents, there are a few keywords which mostly showed up in the "background of invention" section of the documents. Obviously, these patents do not focus on CNT-FED, so we exclude them from the patent network through patent network analysis. However, there are 91 patents and 902 ties in this overall patent network, and this graph doesn't show the relative importance of individual patents clearly. Therefore, the quantitative techniques of technology centrality index and technology cycle time index can be used here to analyze the overall patent network thoroughly.

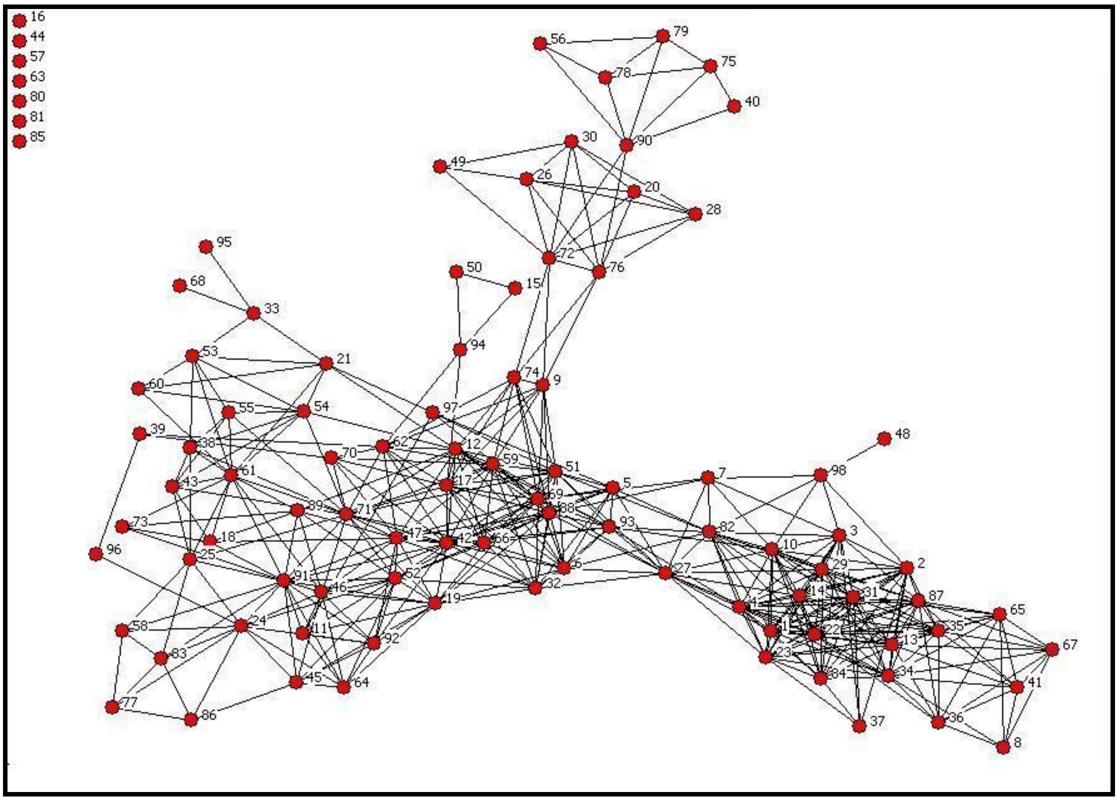


Figure 4.1 Patent network of CNT-FED technology

Technology centrality index (TCI) measures the relative importance of the subject patents. In other words, we can find the more influential patents in the field of CNT-FED by calculating the technology centrality index. The information from analyzing these patents is helpful for revealing the core technologies and developing trends. Table 4.8 shows some relatively important patents in the overall patent network with high TCI values.

Table 4.8 TCI values of the relatively important patents in the overall network level

Patent number (real patent number)	TCI value
71 (U.S. Patent No.6,911,767)	0.2062
42 (U.S. Patent No.6,630,772)	0.2062
69 (U.S. Patent No.6,891,319)	0.1959
87 (U.S. Patent No.7,067,073)	0.1856
88 (U.S. Patent No.7,070,472)	0.1856
91 (U.S. Patent No.7,115,013)	0.1856

From the above measurement, the front six patents with higher TCI values are further classified according to the titles, abstracts and claims of the patent documents. A reasonable explanation is expanded as follows. The patent number 71, 42 and 91 are the first, second and sixth importance of the front six patents. These patents are related to the fabrication processes of FED device, and all the three patents employ the CNT as the emitting material. This result clearly indicates the CNT is an important material for the FED production. In the recent years, CNT based emitter is still the essential factor for industries, academia and government R&D institutes. All the scientists can pay more attention in CNT related subjects to improve the present research regarding the FED fabrication.

Nevertheless, there are two other important patents focused on the whole process of FED fabrication. The patent number 69 and 88 are the third and fifth importance of the front six patents. They claim their major subject on FED device, not the CNT material. For this reason, these two patents directly relate to a field emission device, and more particularly to a FED and methods of forming a FED.

Finally, the fourth importance of the front six patents is numbered 87. This patent emphasizes the preparing and using of phosphor material as the anode in FED. The major subject is about the ZnS-based yellow phosphor, and the application of phosphor can be adjusted by the different composition of activator and coactivators for various displays. The importance of this patent reveals that phosphor is one of the key materials in FED device. Therefore, TCI analysis indicates the key factor of FED fabrication is not only the CNT material, but also the whole process and the phosphor material.

Technology cycle time (TCT) index measures the life cycle status of the subject technology by gauging the median age of the connected patents. The cycle time reflects the trends of technological advancement. Short cycle time reflects faster technology progress; long cycle time reflects slower technology progress. In this study, we calculate the median of age gaps between each subject patent and other connected patents in the overall patent network. TCT varies from 0.73 to 6.10 years in the overall patent network, which shows the fast rate of technological innovation in the field of CNT-FED. Table 4.9 shows short TCT index values (less than 1 year) and long TCT index values (more than 4 years).

Table 4.9 Short and long TCT index values of some patents

Short TCT group		Long TCT group	
Patent number (real number)	index value	Patent number (real number)	index value
58 (U.S. Patent No.6,798,127)	0.73	98 (U.S. Patent No.7,176,614)	6.10
90 (U.S. Patent No.7,102,278)	0.76	5 (U.S. Patent No.5,708,451)	5.63
71 (U.S. Patent No.6,911,767)	0.85	84 (U.S. Patent No.7,052,352)	4.73
55 (U.S. Patent No.6,774,548)	0.85	82 (U.S. Patent No.7,021,982)	4.72
77 (U.S. Patent No.6,975,063)	0.87	7 (U.S. Patent No.5,814,934)	4.34
74 (U.S. Patent No.6,936,972)	0.99	8 (U.S. Patent No.5,844,361)	4.29

In general, the patents which have short cycle time are related to the CNT-FED or the fabrication of FED from the result of TCT index. Because this index indicates the speed of technical advancement of subject patents, the patent number 58, 71, 55 and 77 are faced more rapid technical changes. These inventions relate in general to FEDs, and in particular to FEDs comprising CNTs. Thus, they are directed toward a new cathode for FEDs, methods for making such a cathode and optimal conditions for constructing such a cathode by lowering the threshold field of emission as well as increasing emission current. The scientists and researchers pay their attention to this matter for improving the faster technology progress. This shows that a larger proportion of the basic research in CNT, which is promoted in both academia and industrial, is of immediate relevance for the inventive activity leading to patents in this field.

In addition to above mention, there are still two patents regarding FED production owning short cycle times (No. 90 and 74). This may indicate the FED related industries are quickly developing in recent years, and there are still many problems could be overcome or improve for present process. Therefore, the TCT index can effectively reflect the technological trends through patent analysis, and the CNT fabrication and the FED production process are really the most popular subjects in flat panel display.

In TCT index measurement, the patents which have long cycle time are all related to the phosphor. Owing to the same emission principle for CRT and FED, the current demand in phosphors is mainly promoted for the performance at low voltage. Because the researchers have developed novel phosphor materials and structures for a long time, the phosphor related patents usually have longer cycle time. In the past few years, patents with higher TCT index have made the significant progress for improving the performance of low-voltage phosphors in reducing the power consumption of the displays. And these techniques have shown abilities in developing low temperature processing techniques, new phosphor coating techniques, and low voltage phosphors manufacturing techniques. However, a new fabrication process or anodic pattern is very difficult to establish in recent years. All researchers are moving their resources to create the cathodic materials. Therefore, the technology cycle time will become longer and longer for the phosphor related patents. This phenomenon may further indicate that the TCT index can monitor the changing trends of technological advancement for CNT-FED related subjects. From the above result, TCT index can quickly point out that the popular key factor of CNT-FED fabrication is not only the CNT material, but also the whole process of device production.

4.2.2 Cluster level

Cluster analysis is a statistical analysis technique to create categories that fit observations (Sharma, 1996). In this study, the purpose of cluster analysis is to sort all patents within patent network into several clusters. These clusters can be viewed as reduced-scale patent network of CNT-FED. From the perspective of network analysis, the denser the linkages among patents within a cluster, the more similar or homogenous these patents are in terms of technological contents. In other words, each patent within a cluster may reach a similar technological level and generate a technology package. Furthermore, this study identifies the characteristics of the clusters and important technologies by examining the relationship among the patents in each cluster.

This study adopts cluster analysis to identify several clusters in the patent network of CNT-FED. The data of analysis contains 91 patents within the overall patent network. First, the number of clusters is determined. The optimal number tends to show the largest between-cluster distance and smallest within-cluster distance. If that is the case, the patents in each cluster have a high degree of similarity and at the same time each cluster is heterogeneously discriminated from the other clusters. The pseudo F statistic, the ratio of mean square between clusters to mean square within clusters, is often the criteria used to decide the number of clusters. By looking for local peaks in the value of the pseudo F statistic, the optimal number of clusters is found (SAS, 1990). As Table 4.10 shows, the case of three clusters shows the maximum pseudo F statistic and indicates the optimal number of clusters. Then, the number of patents and which patents in each cluster are identified. As explained above, three different clusters as well as patents within each cluster are determined through the clustering procedure. The detailed information about the three clusters is discussed as follows.

Table 4.10 Comparison of clusters

Number of clusters	Pseudo F statistic
2	8.6
3	14.9
4	11.3
5	10.7
6	10.6
7	10.2

(1) CNT emitter material technology cluster

This cluster is the largest one in the patent network of CNT-FED, consisting of forty patents. These patents all deal with the manufacturing techniques for CNT emitter materials. Thus, this cluster is called CNT emitter material technology cluster. Figure 4.2 shows the relationship among the patents in this cluster.

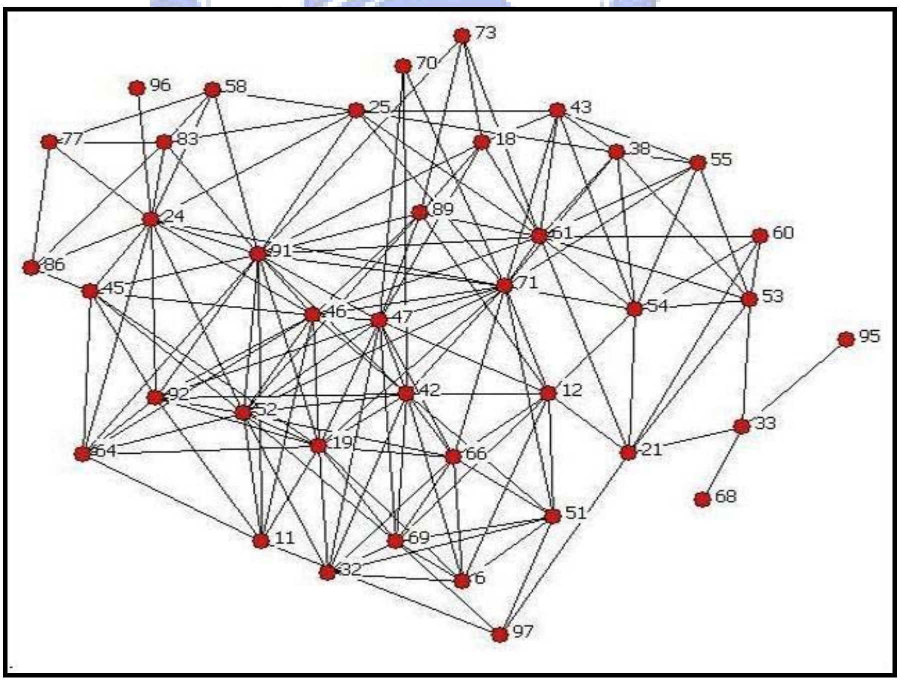


Figure 4.2 Patent network in the CNT emitter material technology cluster

The density index value is 0.188 in this cluster. Compared with the other clusters, this cluster has a medium level of connection. This value shows that CNT based cathodic materials have a high variation in production of field emission devices, and there are still many unknown processes and applications which can be created in the future.

In order to find the more influential patents in the cluster of CNT emitter material, the relative importance of the subject patents are chosen by calculating the technology centrality index. Table 4.11 shows that the TCI values of the relatively important patents in this technology cluster, including patent number 91, 71, 52, 61, 19, 47 and 42. These seven patents consist in the forty patents with index value higher than 0.3415. And the index values of forty patents in this cluster are higher than in overall level. This indicates that the cluster analysis can effectively help for monitoring technological trends in the field of CNT-FED. As intuitive identified in the visual network, these seven patents are all in the central position of whole network. This phenomenon reveals that the higher value can turn out to be the more influential patent in this CNT emitter material technology cluster.

Table 4.11 TCI values of the relatively important patents in the CNT emitter material technology cluster

Patent number (real patent number)	TCI value
91 (U.S. Patent No.7,115,013)	0.4390
71 (U.S. Patent No.6,911,767)	0.4146
52 (U.S. Patent No.6,739,932)	0.3659
61 (U.S. Patent No.6,812,480)	0.3415
19 (U.S. Patent No.6,346,775)	0.3415
47 (U.S. Patent No.6,699,642)	0.3415
42 (U.S. Patent No.6,630,772)	0.3415

The patent number 91, US Patent No. 7,115,013, is entitled method for making a carbon nanotube-based field emission display. Its invention relates to a method for making a FED device, and more particularly to a method for making a CNT-FED device. The main object of this invention is to provide a concrete method for producing CNT-based FED, and a detail procedure is exhibited in this invention. The significance of this patent provides the advantages and novel features of the present invention for other patents or the fabrication of CNT-FED. As anticipated, patent number 52, 61, 19 and 42 also show the relatively high values and describe the method for making a CNT-FED device. In addition, the other two patents, patent number 71 and 47, provide an improved field emission cathode that features treated carbon nanotubes as the emitters by reducing work voltage, increasing emission and increasing emission sites.

(2) Anode material technology cluster

The anode material technology cluster contains twenty-eight patents that deal with anode materials for CNT-FED. Figure 4.3 shows the relationship among the patents in this cluster. The constituent patents of this cluster possess close mutual linkages, and the density index value is 0.409 for this cluster. This phenomenon shows that anodic materials are relatively simple in production of field emission devices, and these patents mainly focus the anodic fabrication on novel phosphor and its deposition in field emission flat panel display.

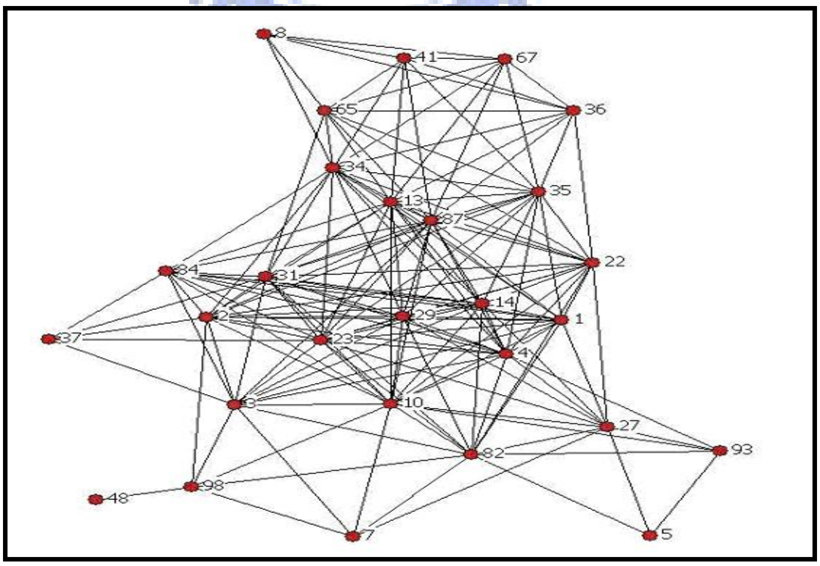


Figure 4.3 Patent network in the anode material technology cluster

In addition, the technology centrality index is also used to find the more influential patents in the cluster of anode material. Table 4.12 shows the TCI values of the relatively important patents in the anode material technology cluster, including patent number 87, 10, 31, 4, 34, 23 and 13; moreover, all these values are higher than 0.6071. According to above result, TCI value in cluster analysis also can effectively monitor technological trends in anode materials. These patents are all highly related to phosphor material or process for manufacturing a phosphorescent screen in FED. Parts of patents focus on phosphors for an electronic display to emit the colors, which are core materials in the display industry, and the others relate to the general field of phosphors for use in FED with particular technology to improve in their efficiency.

Table 4.12 TCI values of the relatively important patents in the anode material technology cluster

Patent number (real patent number)	TCI value
87 (U.S. Patent No.7,067,073)	0.6429
10 (U.S. Patent No.6,015,587)	0.6071
31 (U.S. Patent No.6,500,040)	0.6071
4 (U.S. Patent No.5,697,824)	0.6071
34 (U.S. Patent No.6,517,740)	0.6071
23 (U.S. Patent No.6,409,564)	0.6071
13 (U.S. Patent No.6,129,860)	0.6071

The patent number 87, US Patent No. 7,067,073, is entitled yellow ZnS-based phosphor, process of preparing the same and display device using the phosphor. This invention provides a low harmful ZnS-based phosphor and a process of preparing the ZnS-based phosphor. The main object of this invention is improved color coordinates and luminance for use in low-voltage display devices, and a detail formula is exhibited in this invention. Similarly, the significance of this patent provides the novel features for other patents or the fabrication processes for phosphors. As anticipated, patent number 34 and 13 also show the relatively high values and describe the method for making the improved phosphors which have a prolonged lifetime and improved luminous efficiency when used as an emitting layer in FED devices. In addition, the other four patents, patent number 10, 31, 4 and 23, relate generally to methods for producing a phosphor layer for use in display screen or device with particular reference to improvements in their efficiency or the removal of contaminants from the phosphor screens of such displays.

(3) Whole process and other materials technology cluster

This cluster is the smallest one in the patent network of CNT-FED. Twenty-three patents within this cluster are chiefly concerned with methods for fabricating FED by processes and various materials. Thus, this cluster is named whole process and other materials technology cluster. Figure 4.4 shows the relationship among the patents in this cluster. The density index value is 0.157 in this cluster. Obviously, the connection within this cluster is weaker than the other two clusters. By considering the whole setting of cluster analysis, it is expected that the cluster here may reflect the various manufacturing method of FED. Thus, FED related subjects are still looking forward to further improvement.

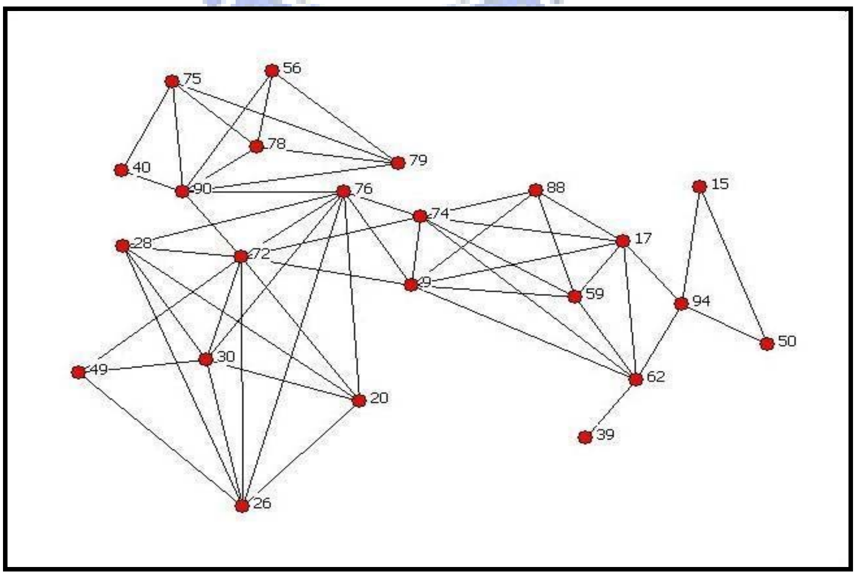


Figure 4.4 Patent network in the whole process and other materials technology cluster

In order to find the critical patents among the whole process and other materials technology cluster, table 4.13 shows the TCI values of the relatively important patents. In this analysis, patent number 72, 76, 9, 74 and 90 show the highest TCI values between 0.3462 and 0.2692. These five patents contain important fundamental technologies for FED fabrication, and they are highly related to carbon-based material.

Table 4.13 TCI values of the relatively important patents in the whole process and other materials technology cluster

Patent number (real patent number)	TCI value
72 (U.S. Patent No.6,922,014)	0.3462
76 (U.S. Patent No.6,956,334)	0.3077
9 (U.S. Patent No.5,973,444)	0.2692
74 (U.S. Patent No.6,936,972)	0.2692
90 (U.S. Patent No.7,102,278)	0.2692

The patent number 72, US Patent No. 6,922,014, is entitled field emission display device having carbon-based emitters. This invention relates to a FED with carbon-based emitters. The main object of this invention is to provide a FED that minimizes diffusion of electron beams generated by electron emitting sources. And a FED is provided that improves the structure of electron emission sources and the configuration for focusing electron beams generated by the electron emission sources, to thereby improve an overall quality of the FED. Furthermore, patent number 76, 9, 74 and 90 also describe the method for making the FED that minimizes diffusion of electron beams generated by electron emitting sources while having the carbon-based material as emitters.

4.3 Technological implications

Regarding the technological implications of CNT-FED technology, first, the developmental path and current states in the area of CNT-FED were analyzed by using the bibliometric analysis on patents. In beginning, the bibliometric data in 98 patent documents were analyzed. And then, we illustrate the growth of invention, the active countries, the active assignees, co-inventorship, productivity of inventors, scientific and technological foundation. Particularly, we observe that the basic technology of producing CNT-FED is finding the way to produce CNTs in higher yields, high purity and better quality by different techniques in the past few years. Highly cited of patents and journals are related to the synthesis, process and production of CNTs for FED application. The emphasis is on the methods that produce high mechanical strength and chemical stability of the nanotubes, which is quite essential from the point of view of application. Some sort of continuous process may probably be needed to grow CNTs on a commercial scale or onto a specific substrate.

Second, the same patents in the area of CNT-FED were also analyzed by using the patent network analysis for the purpose of finding emerging technology and research direction. We draw a network graph of CNT-FED patents based on keywords dealing with CNT-FED technology. From the analysis of data in overall network level, we can obviously distinguish the three portions of highly central patents. This result seems to reflect the actually technological trends which can be taken for three portions in CNT-FED field. They consist of CNT emitter material, phosphor material, and whole process of CNT-FED in the patent network diagram. The specific result was found in TCI and TCT measurements. The developing tendency of world FED production focuses on the fabrication and construction of CNT materials, and this phenomenon indicates that CNT is expected for the ideal material as the emitter in FED fabrication. In addition, the whole process and the phosphor material regarding FED device also play an important role for industrial field.

Finally, the patents were further analyzed in cluster level. Although the measurements in overall network level analysis have pointed out the main subjects of CNT-FED, the cluster level analysis can effectively help for monitoring technological trends in each cluster. The key point, critical bottleneck, and popular direction of each cluster can be rapidly compiled and analyzed by this method. Cluster analysis sort all patents within patent network into three technology clusters. According to the characteristic of clusters, they are named CNT emitter material technology cluster, anode material technology cluster, and whole process and other materials technology cluster, respectively. Obviously, the three clusters not only reflect three portions of critical technologies, but also further provide insights into the technological trends of CNT-FED. The detailed technological implications about each cluster are discussed as follows.

Among the three clusters, CNT emitter material technology cluster as well as whole process and other materials technology cluster have relatively weak connection. This phenomenon shows that the two kinds of technologies have high variation in fabrication of CNT-FED. In other words, there are still many unknown process or various manufacturing method which can be created in the future. In CNT emitter material technology cluster, these patents all deal with the manufacturing techniques for CNT emitter materials. The result clearly indicates that CNT is expected for the ideal material as the emitter in FED fabrication. Moreover, the fabrication and improvement of CNT based emitters are critical trends for CNT-FED technology.

Advantageously, the present analysis indicates a cathode material in field emission display including an electrode comprising very large numbers per unit area of extremely small, preferably elongated composite microstructures that can be applied to a wide variety of large area substrates by simple deposition processes and can be patterned by efficient dry processing methods. And the surface of coating is nanoscopically rough. The coating comprises microcrystallites substantially covering the surface of the microstructures. These many microcrystallites contribute multiple emission sites due to their very high radii of curvature, large numbers, and low work functions. Generally speaking, this coating may comprise crystalline and noncrystalline material. The surface morphology of the roughness features may be in the range of 3 nm to 300 nm in any single dimension. Thus, the material with the characteristic can be used for the future direction in technology viewpoint, and carbon related tube structure is one of the ideal materials in recent development.

On the other hand, whole process and other materials technology cluster are concerned with methods for fabricating FED by process and various materials. The techniques regarding whole process of FED fabrication are quickly developing in recent years, but there are still many problems could be overcome or improve for present process. Comparing with other flat panel displays, FED produces its own light source utilizing colored phosphors. It does not require complicated, power-consuming backlights and filters, and almost all the light generated by a FED is visible to the user. Furthermore, FED does not require large arrays of thin film transistors and large power source, and thus, a suitable assembling process for FED is worth for continuing investigation. And the whole process of FED production can integrate the present manufacturing technology to create the newly FED industry, such as screen printing technique, micro electro-mechanical systems (MEMS) process, integrated circuit (IC) design, and electrochemical deposition. According to above mention, CNT based emitters and FED fabrication related subjects are still looking forward to further development.

In addition, comparing with above two clusters, anode material technology cluster possess close mutual linkages. This phenomenon shows that anode materials related techniques have a low variation for fabrication of CNT-FED. In other words, these techniques are relatively simple in fabrication of CNT-FED. The patents in this cluster mainly focus the anodic fabrication on novel phosphor and its deposition in screen of FED. Due to the same anodic materials for CRT and FED, phosphor material techniques have been developed for a long time. The current demand in phosphors is mainly promoted for the performance at low voltage. In the past few years, however, these techniques have shown abilities in developing new phosphor coating techniques and low voltage phosphors manufacturing techniques. Thus, anode materials belong to more mature technology in manufacturing CNT-FED.

Chapter 5 Results of analyses: Carbon nanotube fabrication

5.1 Results of patent bibliometric analysis

This study uses bibliometric techniques to analyze the status of technological development for CNT fabrication. According to the different aspects of patenting activities such as the growth in patents, country comparison, assignee comparison, inventor comparison, highly cited journals, and highly cited patents, the main goal of this investigation is to quickly understand the developmental path and current states of CNT fabrication.

5.1.1 Growth in patents

Table 5.1 demonstrates the growth in the number of patents for the field of CNT fabrication. From our collected 92 patents, the earliest patent was issued in 2000. The patenting activity is mostly presented from 2003 to 2006 by the issue date, and the majority of patents are filed from 2000 to 2003 by the application date. In general, it takes about one to three years to move from patent application to patent issue. Either the date of issue or application shows that CNT fabrication is still attracting much interest in nanotechnology after 2000. This is confirmed by the fact that Sumio Iijima of the NEC Laboratory in Japan reported the first observation of MWNTs in 1991. After that, significant research efforts in efficient and high-yield CNT growth methods were continually described. The success in CNT growth has led to the CNT related patents, and the electrical and mechanical properties of CNTs have captured the attention of researchers in USA, South Korea, Japan, Taiwan and China. However, the number of patent application decreased after 2004, the reason for the phenomenon may be due to the basic science issues needed to be understood and technological bottlenecks needed to be overcome. Nowadays, the main bottleneck in CNT fabrication is probably one of the main issues either to develop a mass production process or to control growth in order to obtain well-designed nanotube structure. If the trouble is solved, the growth can be expected for the patents and products.

Table 5.1 Growth in patents for CNT fabrication

Application date		Issue date	
Year	Number of patents	Year	Number of patents
1998	1	—	—
1999	6	—	—
2000	13	2000	4
2001	16	2001	3
2002	19	2002	7
2003	27	2003	10
2004	8	2004	15
2005	2	2005	17
—	—	2006	24
—	—	2007	12
Total	92	Total	92

5.1.2 Country comparison

Table 5.2 provides information on the distribution of patenting activity in different countries. USA possesses over fifty percent of our collected patents in the field of CNT fabrication. This result confirms the fact that USA owns the leading status in material science of nanotechnology. In fact, the systematic study of carbon filaments of very small diameters came from the discovery of fullerenes (C_{60}) by Harold Kroto, Richard Smalley, Robert Curl, and coworkers at Rice University, USA before 1991. Of course, a great deal of progress has been made in characterizing and understanding the unique properties of CNT in USA since the Iijima's discovery in 1991. Excluding USA, the other countries in table 5.2 are South Korea, Japan, Taiwan and China according to the number of patents. This means that most Asian countries attach great importance to CNT fabrication research. In addition, it is noteworthy that China filed five patents. It shows that China is starting to pay attention to basic science and nanotechnology, and the CNT fabrication is one of their preliminary works.

Table 5.2 Country comparison in the field of CNT fabrication

Patent application country	Number of patents
USA	49
South Korea	19
Japan	13
Taiwan	7
China	5
Others	4
Total number of all patents of all countries	97
Total number of all patents	92

Note: There is discrepancy between "total number of all patents of all countries" and "total number of all patents" because 5 patents were filed by two countries at the same time.

5.1.3 Assignee comparison

Table 5.3 shows the patenting activity of assignees ranging from corporations, academic institutes, R&D institutes, government institutes, individual, consortiums of corporations and academic institutes, and consortiums of corporations and individuals. The data indicate that corporations are the most active assignees which own 46 patents and occupy 50%; the second are academic institutes which own 25 patents and occupy 27%. Initially, CNTs arouse great interest in the research community because of their strange electronic properties, and this interest continues as other remarkable properties are discovered and promised for practical applications develop by industrials. Since the CNT fabrication belongs to the highly interesting material, not only corporations but also academic institutes play important role in assignee for CNT related basic research.

In order to find out which assignees are the most active in CNT fabrication, each assignee was analyzed further in this comparison. Among corporate assignees, Samsung from

South Korea is the leading corporation with the highest number of patents in the field of CNT fabrication. This confirms that Samsung has controlled the critical technology in CNT fabrication, and this technology was expected to create the marketable product for itself in the future. The second active corporations are NEC from Japan, Iljin Nanotech from South Korea, and Intel from USA. In fact, these corporations enjoy the great reputation in nanotechnology, and all of them take CNT fabrication seriously at this moment. Among the academic institutes, there are 20 patents from USA. This confirms that academic institutes in USA play the important roles in CNT basic research. Moreover, Rice University owns the most patents among these academic institutes. In recent years, it becomes one of the important research institutes in nanotechnology, and this comparison fully demonstrates that Rice University is the pioneer and leader in CNT related research. Among all R&D institutes, most of patents were applied from the Industrial Technology Research Institute (ITRI) of Taiwan for these eight patents. In fact, ITRI is the main R&D institutes in Taiwan, and the manufacturing technology of CNT is one of their developmental directions in applications of field emission displays (FEDs). Among the government institutes, the three assignees are from USA, and all these patents are produced from USA government subsidy plan. Since promoting National Nanotechnology Initiative (NNI) in 2001, USA government has invested huge funds in nanotechnology research, including CNT fabrication.

For the cooperation research, there are 5 patents from the consortiums of corporations and academic institutes. Four of them were filed jointly by Hon Hai Precision Company (Taiwan) and Tsinghua University (China). This shows that there is a good example of cooperation between manufacturers in Taiwan and academic institutions in China. In addition, there are 4 patents from the consortiums of corporations and individual inventors. These patents were filed by Iljin Nanotech and Jang Jin, Iljin Nanotech and Cheol-Jin Lee, Samsung and Young-Hee Lee, and Futaba, Tokai Carbon and Takikawa Hirofumi. Finally, the only one patent, which was filed by inventors Moskovits Martin, Li Jing, and Haslett Thomas, is from individual.

Table 5.3 Assignee comparison in the field of CNT fabrication

Assignee	Number of patents
Corporations	46
Academic institutes	25
R&D institutes	8
Government institutes	3
Consortiums of corporations and academic institutes	5
Consortiums of corporations and individuals	4
Individual	1
Total	92

5.1.4 Inventor comparison

A patent application includes all contributors and researchers as co-inventors who directly contribute to the patentable features in invention (Gupta & Pangannaya, 2000). Table 5.4 indicates the pattern of co-inventorship in the field of CNT fabrication. Only 12 patents are from single inventors, the other 80 patents are from co-inventors. More than half of all patents are from two or three inventors. The remaining patents come from four or more inventors. The highest number of inventors for one patent is 9 persons. It is clear that research in CNT related project is most frequently done by teamwork.

This comparison could be further analyzed to find out the total number of patents owned by each inventor. In other words, it can evaluate the productivity of inventors in these 92 patents, and the detailed result is shown in table 5.5. Eleven inventors produced a maximum number of five patents. Nine of them are Peter Boul, Daniel Colbert, Robert Hauge, Chad Huffman, Jie Liu, John Margrave, Edward Mickelson, Richard Smalley, and Ken Smith from Rice University in USA, and the other two inventors are Won-bong Choi and Young-hee Lee from Samsung in South Korea. However, there are 183 inventors produced only one patent.

The inventors owning only one patent consist of 82.43% of all inventors. This phenomenon means that many inventors are interested in CNT fabrication, but the high productivity of inventors is concentrated on a few inventors.

Table 5.4 The pattern of co-inventorship in the field of CNT fabrication

Number of inventors in each patent document	Number of patents
1	12
2	22
3	25
4	18
5	4
6	3
7	3
8	—
9	5
Total	92

Table 5.5 Productivity of individual inventors in the field of CNT fabrication

Number of patents owned by each inventor	Number of inventors
5	11
4	4
3	5
2	19
1	183

5.1.5 Highly cited journals

The non-patent literature (NPL) cited in a patent can be used to quantify the dependence of a technology on basic science research (Narin & Olivastro, 1988). The citations of NPL, such as citations of journals, are the indicators for studying the degree of linkage between patents and scientific literature (Karki, 1997). For identifying the basic nanoscience knowledge underlying CNT fabrication, this study examines the types and counts of journals that were cited in 92 patents. Table 5.6 shows some highly cited journals listed as sources of scientific information for patentable inventions in these patents. According to the Vinkler (1994) definition, the index of journal references concentration as the percentage share of journals containing 50% of total paper referred to. In this study, 56% of the references are covered by three journals, including Science, Applied Physics Letters, and Nature. These three journals represent 5.3% of the total 57 journals. Thus, they are strong contributors for basic scientific knowledge in the field of CNT fabrication.

Table 5.6 Highly cited journals in the field of CNT fabrication

Name of the journal	Number of citations
Science	158
Applied Physics Letters	115
Nature	110
Chemical Physics Letters	64
Physical Review Letters	24
Nano Letters	21
Others	179
Total number of journals (57)	671

Science is the leading journal of original scientific research in the world and publishes research in various scientific areas, including research on nanotechnology. In addition, Applied Physics Letters is a weekly journal featuring concise, up-to-date reports on significant new findings in applied physics. The letters emphasize rapid dissemination of key data and new physical insights. It can be seen that most basic knowledge of CNT fabrication comes from the latest scientific concepts. Besides, Nature is also publishing the finest research in all fields of science and technology on the basis of its originality, importance and surprising conclusions. The remaining highly cited journals are mostly from fields of applied physics, applied chemistry, and applied materials. So it is evident that the basic scientific knowledge of CNT fabrication comes mainly from physics, chemistry and materials. This phenomenon also illustrates the new invention of CNTs in journals can assist the researchers in synthesis and application of CNTs.

5.1.6 Highly cited patents

The highly cited patents are patents more than average technological impact (Karki, 1997). In other words, the more frequently a patent is cited in sequent patents, the more important for the cited patent. Table 5.7 shows the information on five highly cited patents among all mutually cited patents in the field of CNT fabrication, including patent numbered 3, 6, 2, 1 and 9. These five patents provided important guidance in the early developmental phase of CNT fabrication, and all of them are filed before 2000. These patents all deal with construction or composition for the CNT growth on a substrate, and their fabricating methods are all based on the CVD. Nevertheless, the patent numbered 2, 3, 6 and 9 are especially related to synthesis methods of CNT, and more particularly, to the mass synthesis methods of synthesizing high purity CNT vertically aligned over the particular substrates. The remaining one patent is related to form a cathodic emitter as the electron emission source for FED device.

However, note that the serial numbers of the patents are sorted by the issue date. These five patents have early issue dates. Since citation analysis is age dependent, older patents have more chances of getting cited (Yoon & Park, 2004). Although citation analysis links the relationship of patents, it merely indicates individual links between citing and cited patents. The highly cited patents revealed by citation analysis represent only the important basic technology in the early period. Therefore, it is necessary to further examine the overall relationship among all patents by using patent network analysis in order to grasp the technological trends in the field of CNT fabrication.

Table 5.7 Highly cited patents in the field of CNT fabrication

Patent number (Real number)	Cited frequency
3 (U.S. Patent No.6,146,227)	9
6 (U.S. Patent No.6,331,209)	8
2 (U.S. Patent No.6,129,901)	8
1 (U.S. Patent No.6,062,931)	8
9 (U.S. Patent No.6,350,488)	7

5.2 Results of patent network analysis

In this section, patent network analysis was used to further analyze the overall structures among the patents regarding CNT fabrication. First, we selected keywords from the CNT related patent documents by researchers who have many years of experience in CNT research. Based on their screening, there were 17 keywords, including "chemical vapor deposition or CVD", "substrate", "catalyst", "array", "pattern or patterned or patterning", "gas", "arc discharge", "voltage", "purification", "evaporation", "current", "amorphous", "laser", "crystalline or crystallinity", "modified", "derivatized" and "helium". Second, we counted the occurrence frequency of keywords in each patent document. Because the amount of keywords could be influenced by the length or the total pages of each patent, it was not objective to sum up the occurrence frequency of keywords directly. Therefore, the final value of each keyword should divide the occurrence frequency by the pages of each patent, and then the final values of each patent were integrated into keyword vectors for further analysis. Third, in order to connect the relationship between patents, Euclidian distance could be used to calculate the distance between keyword vectors. All Euclidian distance values among the vectors could be constructed to Euclidian distance matrix, E^d. And then, we transformed E^d matrix into E^s matrix for dichotomizing in the next step. All the values of E^s matrix were from 0 to 1. Finally, the cut-off value, *p*, should be selected to dichotomize the cells of E^s matrix for graphing the patent network. The appropriate cut-off value is necessary to make the structure of the network becomes clearly visible (Yoon & Park, 2004). Through trying out numerous cut-off values, p = 0.18 was chosen, which indicated that I_{ij} equaled 1 if E_{ij}^{s} was smaller than 0.18, otherwise I_{ij} equaled 0. Consequently, the binary matrix, I, was built for the implementation of the network analysis. The patent network were drawn by using UCINET 6.0 (Borgatti et al., 1999) and shown in Figure 5.1.

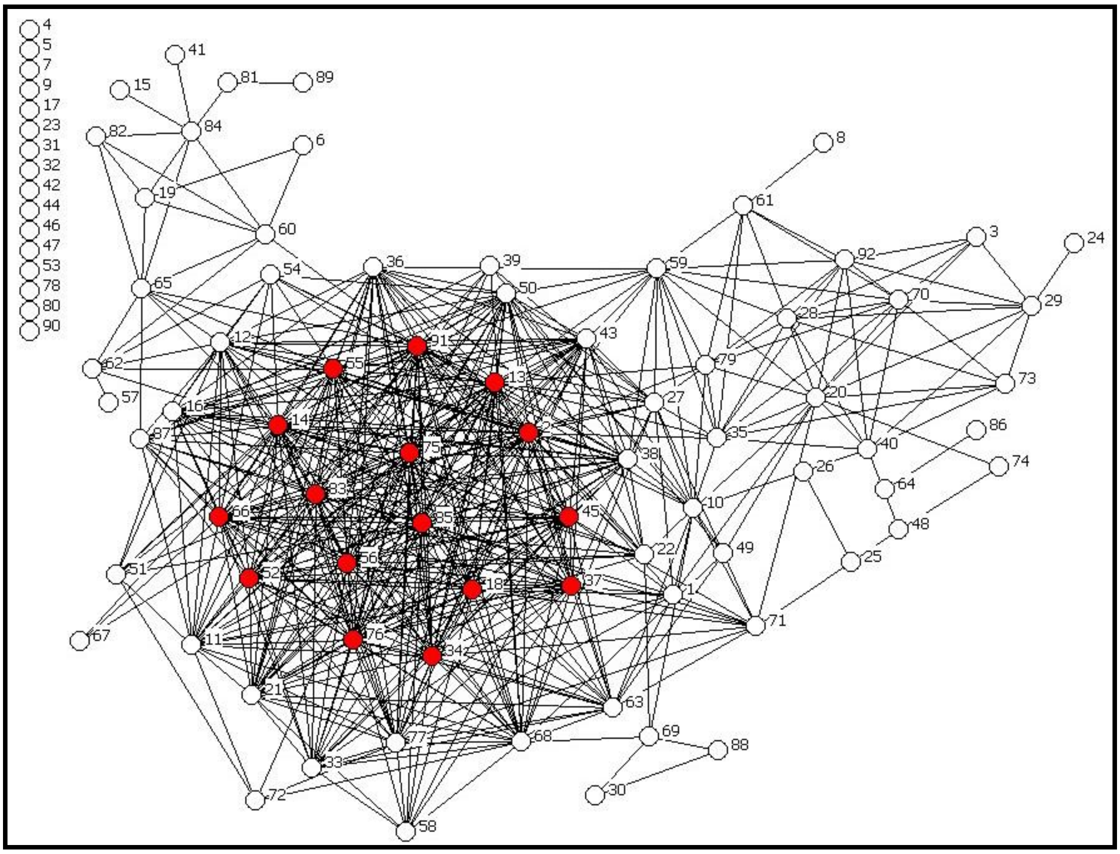


Figure 5.1 Patent network of CNT fabrication

A well-constructed visual display of a network often conveys an intuitive knowledge of a system's structure (Knoke & Kuklinski, 1982). A preliminary visual structure of the overall patent network can be captured by using the graphing approach. Figure 5.1 exhibits the overall patent network in terms of connectivity. This network analysis divides all the 92 patents into two sets, an interconnected set and an isolated set. The interconnected set represents the critical key point of overall patent network, including 76 patents and the relationship among these patents. It provides much information in the fabrication and application of CNT material. Nevertheless, there are still sixteen patents in the isolated set. These inventions relate to the CNT and, more particularly, to the processes for CNT production by various methods, such as arc-discharge, laser ablation, gas phase catalytic growth, and CVD. Among these patent documents, the main purpose of these inventions is to offer the original process for CNT fabrication, including purification process, mass production process, low temperature growth process, thermal conductivity enhancement process, and so on. These progresses in CNT related research have been built upon the successes in material synthesis, but not all the published patents are well suited to the future applications. Obviously, these patents don't well fit the major technological trends in CNT applications, so they are excluded from the network through this patent network analysis.

In this patent network, it can be observed that several patents close mutual linkages intuitively. These patents are located in the center of the patent network and possessed close relationship. They may represent the core technology in the field of CNT fabrication and application. Furthermore, we calculate TCI in order to identify the relatively important patent in this patent network. There are sixteen patents with higher TCI values, including patent numbered 91, 2, 14, 75, 85, 13, 76, 83, 55, 56, 52, 66, 34, 18, 45 and 37. As intuitive identification in the visual network, these patents are all in the central position of whole network. Table 5.8 shows these relatively important patents in the patent network with higher TCI values. These sixteen patents are all over than 0.3, and far ahead of other patents. Through the visual patent network and TCI values, we can find out the relatively important patents. These patents represent the core technologies and the developing trends in CNT fabrication and application. We discuss the detailed meanings further as follows.

Table 5.8 TCI values of the relatively important patents in the patent network

Patent number (real patent number)	TCI value
91 (U.S. Patent No.7,214,361)	0.3956
2 (U.S. Patent No.6,129,901)	0.3846
14 (U.S. Patent No.6,495,116)	0.3626
75 (U.S. Patent No.7,129,513)	0.3517
85 (U.S. Patent No.7,161,285)	0.3517
13 (U.S. Patent No.6,479,028)	0.3407
76 (U.S. Patent No.7,129,554)	0.3297
83 (U.S. Patent No.7,160,530)	0.3187
55 (U.S. Patent No.6,979,244)	0.3187
56 (U.S. Patent No.6,979,433)	0.3187
52 (U.S. Patent No.6,890,654)	0.3187
66 (U.S. Patent No.7,074,260)	0.3187
34 (U.S. Patent No.6,815,294)	0.3077
18 (U.S. Patent No.6,566,704)	0.3077
45 (U.S. Patent No.6,855,603)	0.3077
37 (U.S. Patent No.6,833,567)	0.3077

From the above table, these sixteen patents with higher TCI values are further classified according to their titles, abstracts and claims of the patent documents. A reasonable explanation is expanded as follows. The patent numbered 91 and 2 are the first and second importance of the front sixteen patents. These two patents are related to the CVD method for synthesis of CNT, and both of these two patents employ the metal particle on a growth substrate as the catalyst in CVD process. This result clearly indicates the CVD process is a useful method for CNT fabrication. Unfortunately, current CVD methods of CNT synthesis suffer from a lack of control over the size and shape of the nanotubes. Some methods of CNT production lead to mixtures of SWNTs and MWNTs. Other methods result in production of nanotubes with variations in nanotube shape and size, leading to a lack of control over the properties of the resulting nanotubes.

In order to overcome the above question, the patent numbered 91 proposed using metal nanoparticles as the growth catalyst in the progress of CNT fabrication. The size of CNT was grown by controlling the size of the metal nanoparticles. Therefore, many works used this process to obtain the SWNTs while the size and properties of the CNT should be controlled in their research. Up to now, controlling CNT fabrication is still the essential factor for industries, academia and government R&D institutes. All the scientists will pay more attention in this subject to improve the present research and application.

Furthermore, the patent numbered 14, 13, 52 and 56 are also improving the usual synthesis process to make net shape CNTs, accelerate production, make encapsulated CNTs, and synthesize CNTs by unseeded process. These inventions might have more chances to become real marketable applications in the near future. And the areas where predicted or tested CNT properties appear to be exceptionally promising are mechanical reinforcing and electronic device applications.

The electrical and mechanical properties of CNTs have captured the attention of researchers worldwide. Understanding these properties and exploring their potential applications have been a main driving force for this area. For this reason, many synthesis processes were modified to improve their unique and useful structural properties. For the patent numbered 2, it describes a novel method of filling the inner cavity of the nanotubes with metals by electroless plating technique. However, CNTs filled with metallic or semiconducting particles might serve as the constituents of novel materials with useful catalytic, magnetic, electrical or electronic properties, and energy storage characteristic leading to new devices, such as the patents numbered 66 and 83. In patent numbered 83, SWNTs can be used for reversibly storing hydrogen. Additional advantages by filling metal particles can realize if the hydrogen adsorption and desorption process occurs without the need for high energy input, hence marking the SWNTs amenable for use as hydrogen fuel cells. Besides, as for patent numbered 66, the main invention of this patent is to provide a filter for use in an air conditioner, which indicates CNTs, in which nano-sized metal particles are deposited into each CNT. These metal particles use their catalytic ability to sterilize, remove odors and volatile organic compounds from air, or combinations.

Finally, the other eight patents are related to the application of CNT material in recent years, including numbered 75, 85, 76, 55, 34, 18, 45 and 37. CNTs can be utilized individually or as an ensemble to build functional device prototypes, as has been demonstrated by many research groups. Ensembles of CNTs have been used for the field emission based flat-panel display and the composite materials with improved mechanical and electromechanical properties in actuators. Bulk quantities of CNTs have also been suggested to be useful as high-capacity hydrogen storage media. Individual CNTs have been used for field emission sources, tips for scanning probe microscopy and nano-tweezers, CNTs also have significant potential as the central elements of nano-electronic devices including field efficient transistors, single electron transistors, rectifying diodes, and switching devices.

From this patent network analysis, TCI can help us to realize the technological trends in the field of CNT fabrication and application. The full potential of CNTs for applications will be realized until the growth of nanotubes can be optimized and well-controlled. Real-world applications of CNTs require either large quantities of bulk materials or device integration in scaled-up fashions. Therefore, the front sixteen patents in TCI analysis reveal that fabrication and application of CNTs have the same importance in the future. The researchers work for different goals should pay the same attention in these two areas. For materials such as composites and hydrogen storage, it is desired to obtain high quality CNTs at the kilogram or ton level using growth methods that are simple, efficient and inexpensive. For devices such as CNT based electronics, scale-up will unavoidably rely on self-assembly or controlled growth strategies on surfaces combined with microfabrication techniques. Significant work has been carried out in recent years to tackle these issues. Nevertheless, many challenges remain in the nanotube growth area after TCI analysis. First, an efficient growth approach to structurally perfect nanotubes at large scales is still lacking. Second, growing defect-free nanotubes continuously to macroscopic lengths has been difficult. Third, control over nanotube growth on surfaces should be gained in order to obtain large-scale ordered nanowire structures. Finally, there is still a seemingly formidable task of controlling the chirality of single-walled CNTs by any existing growth method. In this way, development of functional devices based on CNTs will surely have a significant impact on present and future technology needs.

TCT index indicates the life cycle status of the subject technology by measuring the median age of the connected patents. TCT reflects the trends of technological progress. The short TCT reflects faster technology progress, but long TCT has the opposite result. The changing trends of technological progress in CNT fabrication and application should be monitored by this analysis. In this study, we calculate the median of age gaps between each subject patent and other connected patents in the whole patent network. TCT value varies from 0.67 to 4.02 years in this patent network, which shows the different rates of technological innovation in the synthesis and use of CNTs. Table 5.9 shows the eight patents which own the shorter TCT index values (less than 1 year) and Table 5.10 lists the front five patents with long TCT index values (more than 3 years).

Table 5.9 Short TCT index values of some patents

Patent number (real patent number)	TCT index value
39 (U.S. Patent No.6,835,613)	0.67
33 (U.S. Patent No.6,812,480)	0.85
62 (U.S. Patent No.7,029,751)	0.91
22 (U.S. Patent No.6,645,455)	0.95
68 (U.S. Patent No.7,084,507)	0.96
60 (U.S. Patent No.7,011,884)	0.96
84 (U.S. Patent No.7,160,531)	0.96
82 (U.S. Patent No.7,157,069)	0.99

Table 5.10 Long TCT index values of some patents

Patent number (real patent number)	TCT index value
48 (U.S. Patent No.6,863,942)	4.02
59 (U.S. Patent No.7,011,760)	3.43
2 (U.S. Patent No.6,129,901)	3.40
3 (U.S. Patent No.6,146,227)	3.34
54 (U.S. Patent No.6,930,307)	3.33

From the result of TCT index, the patents which have short TCT are related to the modification and utilization of CNTs for further industrial applications, and this index can provide the speed of technological innovation in this patent network. The patents with short value are numbered 22, 33, 39, 60, 62, 68, 82 and 84 which can be divided into three groups including CNT based devices, CNT modification, and CNT production.

The patents numbered 33, 39 and 68 are classified into CNT based devices, and these inventions relate to methods of producing integrated circuits and FED. This is because CNT exhibits a variety of desired electronic properties. The electronic properties can be controlled by the diameter, number of walls, and defect density of the CNT, and the methods of fabricating allow for the CNT to be positioned at specific locations on circuit structures to fulfill specific electronic functions such as forming electric interconnects, diodes, transistors and micro patterns. The formation method of CNT using arc discharge or laser ablation is not suitable for the production of integrated circuits. The method using a CVD process herein has feasibility for application to the production of integrated circuits. Furthermore, the CNT based emitting source is positioned on the exposed cathode layer, and CNT paste is prevented from remaining during development, thereby preventing current leakage and short circuit between the electrodes and diode emission. Accordingly, the performance of the FED device can be improved by the fabrication of CNT. From above analysis, the scientists and researchers pay their attention to this matter for improving the technology progress. This shows that a larger proportion of the CNT based subjects, which are promoted in both academia and industrial, is of immediate relevance for the inventive activity leading to patents in this field.

In addition to above mention, another three patents regarding CNT modification production owning short values (No. 22, 60 and 68). Since the discovery of CNTs, researchers have been searching for ways to manipulate them. While there have many reports and review articles on the production and physical properties of CNTs, reports on chemical manipulation of nanotubes have been slow to emerge. This may indicate the functionalizing nanotube is hard to develop in the beginning of CNT related research, and there are still many problems should be overcome or improve for the fabrication process. In recent years, the requirements of CNT materials suddenly increased, more and more researchers face up to the facts of modification the CNT structure for the further application. For this reason, the CNTs with chemically functional group, specific isotope and graphite out layer are attached great importance to production, and the related patents own the short TCT in this patent network analysis.

Finally, the other two patents with short TCT (No. 82 and 84) are related with aligned CNTs and combustion synthesis of CNTs to improve the production in a catalytic CVD process. Recent interest in CVD nanotube growth is also due to the idea that aligned and ordered nanotube structures can be grown on surfaces with control that is not possible with arc-discharge or laser ablation techniques. Aligned CNTs have application in numerous areas of composite materials, such as for use in separation media, catalysts, catalyst supports, energy storage and electronic applications for FED device, Electromagnetic Interference (EMI) shielding, sensor components, and electronically conductive plastics. Besides, some researchers have tried to synthesize CNTs using flame instead of the previous methods in CNT production. The related patents provide apparatuses and processes for the combustion synthesis of CNTs without using vacuum by allowing an oxidizing agent, a fuel, and an inert gas to form the inverse diffusion flame in a combustor. As the fuel exists outside the flame zone, it is possible to directly collect samples of CNTs and a substrate may be installed with ease. Moreover, the manufacturing costs can be significantly lowered to a level suitable for mass production so that CNT technology can be extended to various applications. Therefore, the result of TCT index with lower value can effectively reflect the present technological trends, and the CNT based devices, CNT modification, and CNT production process are really the most popular subjects in industrial applications of CNTs.

In addition to the patents with short TCT index value, the front five patents with long TCT index value are listed for further discussion. These patents are numbered 2, 3, 48, 54 and 59. These five patents are still related to the CNT fabrication in a CVD process, but their innovation focuses the controlling synthesis of CNTs on using different situations. Since the first observation of CNTs, numerous papers have reported studies on the yield of well-graphitized nanotubes, diameter and wall thickness, growth mechanisms, alignment, electron emission properties, nanodevices, theoretical predictions, and potential applications. Selective positioning and growth of CNTs are necessary for future integration with conventional microelectronics as well as the development of novel devices. Alignment of the CNTs is particularly important to enable both functional studies and applications. However, limited progress has been reported in the controlled placement of nanotubes. The patents with long TCT index value indicate the above phenomenon in this analysis.

The patents numbered 48, 54 and 59 describe the CNT fabrication onto the different substrates. Specifically, vertical alignment has been an important goal due to its technological importance for applications such as scanning probe microscopy, microelectronmechanical manufacturing system (MEMS) devices, and field emission flat panel displays. Until now, there is still no more effective solution which can manipulate nanotubes for above applications. Because these techniques are difficult and labor intensive, in situ aligning of nanotubes during growth onto the porous substrates including foam, felt, mesh and membrane have been attempted. However, the reactions and the synthesis of these materials in novel combinations with varying substrates or coatings cannot be easily achieved. Therefore, the techniques of making above structures are always disclosed as patents with longer TCT.

Furthermore, the patents numbered 2 and 3 also describe the CNT fabrication regarding the controlling synthesis of CNT onto alumina template and MEMS device. The similar technical advantage of these two patents is that the method of these two inventions is designed to produce aligned CNTs with controlled shape, diameter, wall thickness, length, orientation, and location of growth. Although these two patents are filed and applied for long time ago, their main invention is still the critical factor for the controlling synthesis of CNT on a substrate. For this reason, it is very reasonable for these two patents owning the long TCT index value. But there are still some problems needed to be solved in the future, the final goal of these two inventions is applied for the industrial applications.

Even if it is important for creating a new fabrication process for CNT, a new method is very difficult to establish in recent years. All researchers are moving their resources to create the application of CNT related products. Therefore, TCT will become longer and longer for the fabrication process research. This phenomenon may further indicate that the TCT index can monitor the changing trends of technological advancement for fabrication and application of CNT. And the TCT index value can quickly point out that the object in mind for CNT materials is modified the CNT structure to improve the whole process of device production.

5.3 Technological implications

Regarding the technological implications of CNT fabrication, first, the developmental path and current states in the area of CNT fabrication were analyzed by using the bibliometric analysis for all patents. From the analysis result, the main growth methods of producing CNT are classified for laser ablation, arc-discharge, and CVD methods. Although the CNT material was observed from the year of 1991, the fabrication process is still attracting much attention after 2000. The key technology of CNT fabrication is finding the way to produce CNTs in higher yields, high purity, well conformation, and better quality by different techniques in the past few years. The highly cited of patents and journals are related to the synthesis, process and production of CNTs by CVD process, and the growth of nanotube materials by CVD in bulk and on substrate were also mentioned.

Second, the same patents were also analyzed by using the patent network analysis for the purpose of finding critical technology and research direction. The network graph was obtained from the keywords of CNT related patents regarding the growth of CNT. From this result, a major portion of patents in the center of network graph can be obviously distinguished, and it seems to reflect the actually technological trends. This portion represents the truth that major purpose of CNT production is in the field of CNT fabrication and application. The similar result was found in TCI and TCT measurements. The developing tendency of world production focuses on the fabrication and application of CNT materials, and this phenomenon indicates that CNT is expected for the ideal material to meet the future industrial request. In addition, the CVD process plays an important role for manufacturing CNT based device in industrial field. Therefore, it is without doubt that patent documents are a valuable resource of technical and commercial knowledge. The potential of patent data can be easily realized from this analysis, and the market demand and the future direction can also be expected.

Finally, this study reveals the critical technologies for growing the CNT materials generally fallen into two categories: (1) enhancing the characteristic of CNT with various methods, and (2) producing CNT by CVD method on various substrates. Since the discovery of CNT, several researches have suggested potential applications of CNTs. These include the use of CNTs as electron field emitters for vacuum microelectronic devices, individual MWNTs and SWNTs connected to the end of an atomic force microscope (AFM) tip for use as nanoprobe, MWNTs as efficient supports in heterogeneous catalysis or as microelectrodes in electrochemical reactions, and SWNTs as good media for lithium and hydrogen storage. Some of these inventions could become real marketable applications in the near future, but others need further modification and optimization. Areas where predicted or tested the CNT properties appear to be exceptionally promising are mechanical reinforcing and electronic device applications. The lack of availability of bulk amounts of well-defined samples and the lack of knowledge about organizing and manipulating objects such as CNTs have hindered their progress in developing these applications. The last few years, however, have seen important breakthroughs that have resulted in the availability of nearly uniform bulk samples. There still remains a strong need for better control in purifying and manipulating CNTs, and the development of functional devices or structures based on CNTs will surely have a significant impact on future technology needs.

Chapter 6 Conclusions

CNT-FED is a new generation of flat panel display. It represents both novel application of nano-technology and revolutionary invention of display. Especially, CNTs which possess extraordinary mechanical, electronic and thermal properties are core emitter materials in the structure of CNT-FED. The methods of CNT fabrication play the important role for the manufacturing process of CNT-FED. Although CNT-FED has many advantages and potential, several technological bottlenecks need to be overcome before further progress. Thus, it is necessary to monitor the states and trends of CNT-FED technology and CNT fabrication before the next stage of technological development. Through a series of analytical processes, the results of this study grasp the key technologies of CNT-FED and CNT fabrication as well as provide hints regarding future technological development. In this chapter, the contributions of this study as well as the limitations of this study and the recommendations for future study are discussed as follows.

6.1 Contributions of this study

This study uses patent bibliometric analysis and patent network analysis to monitor the states and the trends of CNT-FED technology and CNT fabrication. These applications not only demonstrate the usefulness of the patent analyses, but also illustrate the states and the trends of technological development for CNT-FED technology and CNT fabrication successfully. Some important outcomes regarding technological trends and methodologies are concluded as follows.

There are several important insights about CNT-FED technology and CNT fabrication. Regarding CNT-FED technology, this study indicates that three critical technologies including deposition CNT on substrate, coating phosphor on screen, and assembling process for whole device are playing the important role for CNT-FED fabrication. The mainly developing trend of CNT-FED technology focuses on the fabrication and construction of CNT materials. Furthermore, this study reveals the approaches for making a CNT-based FED generally by two categories; one is replacing the field emitter with an alternate material, and another is field emitter design without traditional technology. For the next generation FED, researchers have directed efforts towards reducing the overall display cost by replacing the metal emitter with alternative cold field emitters, such as CNT-based materials. Alternative materials provide a cost benefit if the switching voltage is reduced below the 20-60 volt range, thus allowing the use of smaller, less expensive driver ICs. Improved emitter materials also benefit displays if they can be incorporated in the display at a lower cost, or if they allow larger features with better yield due to their improved performance. For this purpose, researchers have to investigate materials which possess either a lower electron work function or a larger intrinsic field enhancement.

Regarding CNT fabrication, this study indicates that CNT is expected for the ideal material to meet the future industrial request. The mainly developing trend of CNT fabrication focuses on CVD technique. Especially, the CVD technique plays an important role for manufacturing CNT based device. Furthermore, this study reveals the critical technologies for fabricating the CNT materials generally by two categories; one is enhancing the characteristic of CNT with various methods, and another is producing CNT by CVD method on various substrates. From this analytical result, however, the growth mechanism of CNTs is a mystery. It is not really possible yet to grow these structures in a controlled condition. Even if there have been some successes in growing CNTs through tuning the growth conditions by trial and error, the general challenge for developing CNTs is still applied this material to functional devices and structures. In addition, another challenge is in the manipulation of CNTs. Nanotechnology is in its infancy and the revolution that is unfolding in this field relies strongly on the ability to manipulate structures at the atomic scale. This will remain a major challenge in this field, among several others.

In addition to the analytical findings, there are many interesting results with regard to methodologies in this study. First, patent bibliometric analysis assists the researchers in easily understanding the developmental states of the subject technology through looking at different aspects of patenting activities. Second, patent network analysis can visually display all the relationship among the patents. The visualization of the network enables the researchers to intuitively comprehend the overview of a set of patents in the field of the technology being studied. Third, both TCI and TCT measurements can clearly show the information at the overall network level. TCI can be used to identify the influential patents, and the information from analyzing these is useful for revealing the critical technologies and the developmental trends. On the other hand, TCT index calculated from the degree of newness of patents can help the researchers to point out the changing trends of technological advancement. Finally, the cluster level analysis can effectively assist the researchers in understanding the characteristics of the clusters and managing the technology packages.

Particularly, patent network analysis, an advanced technique of patent analysis, displays overall analytical results. We proposed a detailed process of generating a patent network and conducting the ensuing quantitative analysis. The advantages of this method are demonstrated fully in this study. Primarily, it combines three types of patent analysis including patent indicators, patent classification, and patent maps to get more rich information in the field of emerging technology. Moreover, it grasps the internal structure of patent network because it takes several keywords as input base. Also, the visual information is more easily comprehended and remembered. Finally, it indeed facilitates analysis of up-to-date trend of emerging technologies.

In order to extract hidden information from the raw database of patents, it is necessary to apply varieties of methodologies. Undoubtedly, the fruitful methodologies that were applied in this study are helpful for the analyses of technological states and trends. The patents selected by these analyses express important insights in technology management. The methodologies of this study contribute to monitor the emerging technology. Furthermore, combining patent bibliometric analysis with patent network analysis offers a useful research avenue for the area of patent analysis.

6.2 Limitations of this study and recommendations for future study

There are still several limitations about methodology in this study. First, the relevant patent keywords which were used in patent network analysis are selected by technical experts. Even if these experts have rich experience in the research fields of CNT-FED and CNT, it is hard to avoid the subjectivity. Second, the degree of connectivity in the patent network is decided based on the cut-off value. This study selects a reasonable cut-off value so that the structure of the network becomes clearly visible, but the determination of cut-off value is also in nature a subjective task. Finally, it may be difficult to generate a patent network if the size of patent documents is too voluminous.

Nevertheless, the relative advantage of patent network analysis is substantial and the utility of this method has been elaborated in this study. In order to make the visual method more concrete, however, it is necessary to modify the method into more sophisticated one. For future study, some promising issues are recommended as follows. First, the use of data mining technique is suggested to extract patent keywords. Second, the relative importance of patent keywords needs to be distinguished. Third, a sensitivity analysis can be used to determine the cut-off value. Finally, the development of other quantitative indexes is required to expand the scope of analysis.

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簡　　歷

姓　　名：吳肇展（Chao-Chan Wu)

出 生 地：台灣基隆

出生日期：1975 年 8 月 29 日

學　　歷：國立交通大學經營管理研究所博士

國立交通大學經營管理研究所碩士

東吳大學國際貿易學系學士

國立台北商業專科學校會計統計科

學術著作：

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