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A systematic approach for integrated trend analysis—The case of etching

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ABSTRACT

Understanding technology development trends is of critical importance to countries, industries and enterprises to be sustainable in global competition. Attempts have been made to establish trend analysis by bibliometric and patent analyses. Also text-mining uncovers hidden and important information from structured or unstructured documents which serve as knowledge carriers. This study aims to provide a systematic approach for integrated trend analysis that takes into account bibliometric analysis, patent analysis and text-mining analysis. Etching is selected as the case study for integrating trend analysis method proposed in this study. Also, validity and applicability of the integrated analysis are evaluated.

1. Introduction

Competitions are universal activities that every actor encounters in society. In order to survive the rigorous competition and for sustainable global growth, nations and enterprises make various strategic decisions by the use of industry competition analysis, enterprise competition analysis, market analysis, and technology forecasting. In this fast-paced technological environment, it is essential for enterprises in technology industry to understand methods to achieve sustainable market growth. Introducing R&D resources at early stages and continuously reviewing business strategies are two important factors for sustainable business growth.

It can be understood from Martino's stage of innovation [1], shown in Fig. 1, that no invented techniques directly jump from idea to practical application. The processes illustrated in Fig. 1 comprise of several stages for continuous enhancement of practicability and usefulness, namely the stages of innovation. The understanding of the development context composed of these stages of innovations and the early R&D resource investments are keys to sustaining entrepreneur competitiveness.

In Fig. 1, the first stage is *Basic Research* and it is the discovery of new knowledge and is not necessarily for any practical application. The second stage *Applied Research* is the invention of new methods or new potential applications with specific practical purposes. The third stage *Development* refers to the product in the process of commercialization, and puts emphasis on developing new products, improving manufacturing procedures, and increasing yield rates. The fourth stage is the “*Application*” where the product is applied and is analyzed for *Social Impact* which is the fifth stage. The iteration like process for technology innovation triggers knowledge diffusion in different mechanisms associated with the mentioned five stages. The carrier of knowledge changes from paper, to patent to newspapers, etc., as the innovation proceeds through the next stages as illustrated in Fig. 2.

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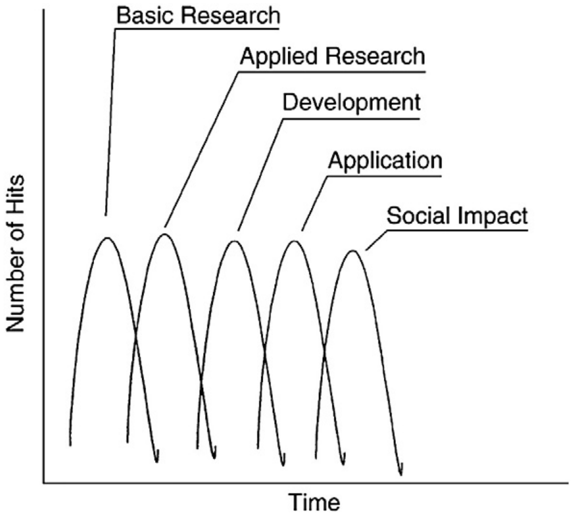

Fig. 1. Bibliometrics estimate of stage of innovation [1].

1.1. Knowledge carrier-based trend analysis

Knowledge carrier-based trend analysis is of great importance in technology forecasting because it provides a way to plan future strategies for smoothing technological innovation. For example, technological forecasting can obtain: 1) the functional differences among new techniques, 2) the time of future technological breakthrough, 3) the possible solutions for future problems, 4) the direction, trend and perspective of future techniques, 5) the future market share, and 6) the future impact on market, social and economic environment, etc. [2–4].

Porter summarized the five most frequently employed families of technology forecasting: 1) monitoring, 2) trend analysis, 3) expert opinion, 4) modeling, and 5) scenario construction [5]. This study aims to understand technology development by the trend analysis method. Important characteristics of the trend analysis method as summarized by Porter are shown in Table 1.

As shown in Fig. 2, technological development has different stages of innovation. Trend analysis which basically forecasts trends of innovation at each stage should be based on different data sources (knowledge carriers) which are associated with each stage of innovation. While the knowledge carriers required in technological development change with each stage, the two most important knowledge carriers for trend analysis with bibliometric and patent methods are scientific papers and patents. In addition, knowledge is coded by text in every knowledge carrier hence *text-mining* is a very popular method to uncover information hidden in coded documents. It is also a rapidly developing methodology for trend analysis. The three important methods for trend analysis are discussed in the following sections.

1.1.1. Bibliometric analysis

Methodologies have been proposed and applied into various knowledge fields for understanding paradigms or the dynamic development of knowledge [6]. The methodology that is used for this purpose is bibliometric analysis on the basis of literature publication metadata and information. For example, bibliometric analysis of pharmacology and pharmacy journals [7], global stem cell research trend [8], research on mental health in the workplace [9], nanotechnology innovation system [10], hydrogen energy [11] and ocean circulation [12], etc.

1.1.2. Patent analysis

Patent analysis is the use of statistical methods to convert patent information into useful knowledge and can be applied at different levels, i.e. country, industry, enterprise, and technological field. The use of patents for trend analysis can be easily found in the trend analysis literature; for example, strategies of patenting activities and patent managements for Taiwan and Korea [13],

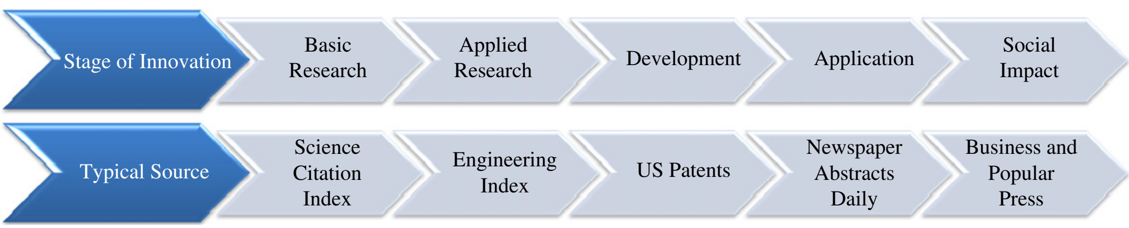

Fig. 2. Stages of innovations and data sources [1].

Table 1
Characteristics of trend analysis method [5].

Description	Trend analysis uses mathematical and statistical techniques to extend time series data into the future. Techniques for trend analysis vary in sophistication from simple curve fitting to Box–Jenkins techniques.
Assumption	Past conditions and trends will continue in the future more or less unchanged
Strengths	It offers substantial, data-based forecasts of quantifiable parameters and is especially accurate over short time frames.
Weaknesses	If often requires a significant amount of good data to be effective, works only for quantifiable parameters, and is vulnerable to cataclysms and discontinuities. Forecasts can be very misleading for long time frames. Trend analysis techniques do not explicitly address causal mechanism.
Uses	To project quantifiable parameters and to analyze adoption and substitution of technologies.

nanopatenting patterns in relation to product life cycle [10], environmental technology innovation in China [14], fuel cell and nanotechnology industries [15], electrical conducting polymer [16], and combination of bibliometric analysis and patent analysis [17].

1.1.3. Text-mining analysis

Text-mining is the process to discover previously unknown information by automatically extracting information from various unstructured data [18]. Benefits of text-mining can be seen in the areas where there is large amount of textual data, e.g. research papers or patent document, are available. Scientific areas that have used text-mining technique to understand their technology trajectories are, information security [19], systems biology [20], drug discovery [21] and to map spices research [22]. Also, text-mining was applied on patent to investigate DNA Chips [23] and product innovative process [24], etc.

1.2. Research purpose

According to Martino's stages of innovation [1], basic research comes earlier than technological development. Martino's widely accepted theory suggests that technology gets more mature and that knowledge naturally diffuses from basic research to technological development as time goes by. This study investigates if there are any factors affecting knowledge diffusion at various stages of innovation.

In literature bibliometric analysis, patent analysis and text-mining are widely used to investigate scientific papers and patents. Even though all the three methodologies have individually been effective in the field of trend analysis but none of them alone is sufficient enough to provide an in-depth analysis without combining them with other methodologies. Therefore, the purpose of this study is to integrate bibliometric analysis, patent analysis, and text-mining analysis and systematically analyze both scientific papers and patents. The study also aims to analyze technology development trends by using this integrated method. An important technology is selected as the target to have its development trend investigated by the integrated method. Also, the relations among framework components of this integrated method are discussed to provide insights into this systematic approach and contribute substantially to the potential development of more advanced bibliometric methods in the future.

1.3. Research target

Based on the reasons given below etching has been selected as the research field to be investigated in this study.

1) The two important and representative industries using nanotechnology are “semiconductor industry” and “Micro Electro-Mechanical System Industry”. However, etching is a technique that is widely used in these fields and plays a very important role in Semiconductor, Micro Electro-Mechanical System, and other nanotechnology related industries.
2) With over 40 years of development, Taiwan's *semiconductor industry* has built a complete ecosystem providing solid semiconductor foundations. Etching is a critical technology for patterning fine line-width semiconductor topology and is regarded as one of key technologies for sustaining Taiwan's semiconductor industry.
3) Also, our practical experiences on etching enable us to obtain much deeper insight into etching and test the validity of the integrated trend analysis method proposed in this study.

The questions to be investigated and answered in this study are; for example: 1) How different are the results between bibliometric analysis and text-mining analysis? 2) Are trend analysis methods complementary to each other? 3) What are external factors affecting technological development? 4) What is the global development trend of etching? 5) What is Taiwan's position in this globe? 6) Is there any relation between paper life cycle and patent life cycle?

2. Research method

Research methods in detail are discussed in following sections: 1) research framework, 2) research process, 3) research target, 4) research tool and 5) database query strategy.

2.1. Research framework

Fig. 3 illustrates the six dimensions considered systematically as the research framework. This study discusses the mechanisms of the trend analysis methodologies as well as the correlation between the analysis methods and the two databases on the basis of the six dimensions.

2.2. Research process

The research process flow chart of this study is shown in Fig. 4. This is an integrated methodology to apply bibliometric analysis, patent analysis, and text-mining analysis on both the scientific paper database and the patent database. The results obtained from scientific paper database and patent database are integrated to understand the technology development trend. For bibliometric analysis and patent analysis the number of papers as a function of time, country, organization, and subject area is investigated. For text-mining analysis, keyword trend and knowledge map are investigated. The field of "etching" is selected as the platform for investigating the correlation between trend analysis methods and databases.

2.3. Research target

"Etching" is the target field to study science and technology development trends. SCIE (Science Citation Index Expanded) is selected as the data source for scientific trend analysis (also named as bibliometric analysis or paper analysis in this study) and US patents from DWPI (Derwent World Patents Index) are selected as the data source for technological trend analysis (also named as patent analysis in this study). Publication period for both papers and patents is from 1978 to 2007. The reasons for the selections are:

1) SCIE: The Science Citation Index (SCI) database owned by Thomson Reuters is the most well known and widely used database in bibliometric analysis community. Journals collected in SCI database are top academic journals. The larger version (Science Citation Index Expanded) covers 6400 of the world's leading journals across 150 disciplines [25].
2) DWPI: The DWPI (Derwent World Patents Index) is the world's most comprehensive database of enhanced patent documents. DWPI patent titles and abstracts contain concise, descriptive, English-language sentences written by experts to highlight the content and novelty of the invention disclosed in the patent. This provides more comprehensive results when conducting text-mining analysis [26].
3) US patent: Patents are territorial in nature. US is one of the biggest consumer market in the world and a lot of business enterprises file patents in the US in order to obtain intellectual property rights for their product sold in the US. The use of US patents is the most reliable approach to understand the trend of technology development in the globe.
4) Time span: This study selects a time span of 30 years, 1978–2007, which is long enough to cover the development of etching.

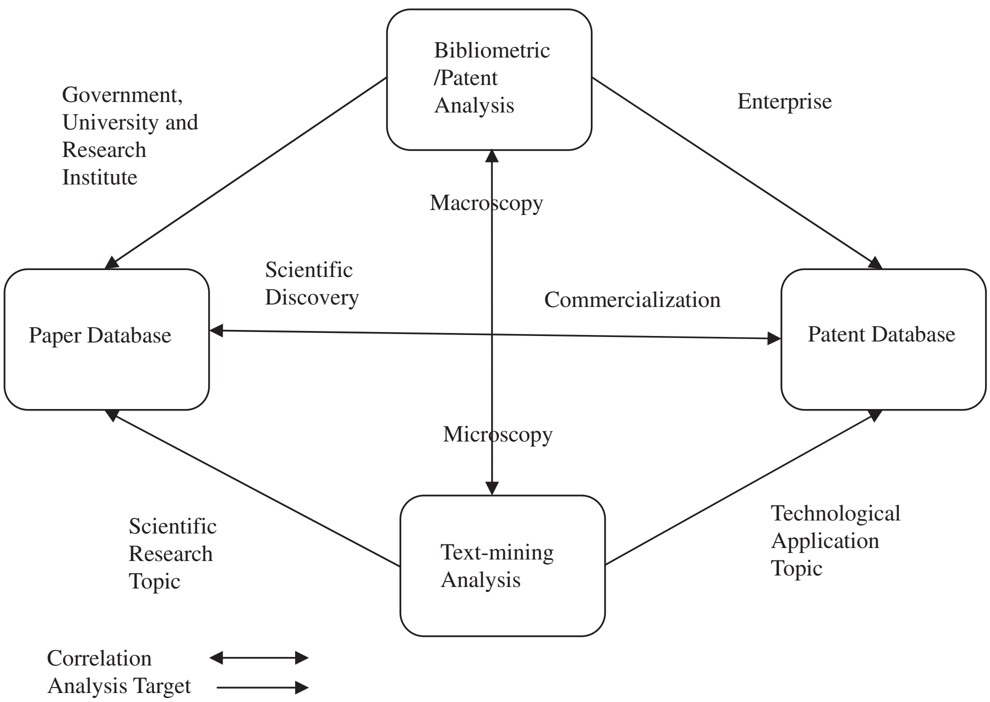

Fig. 3. Research framework of this study.

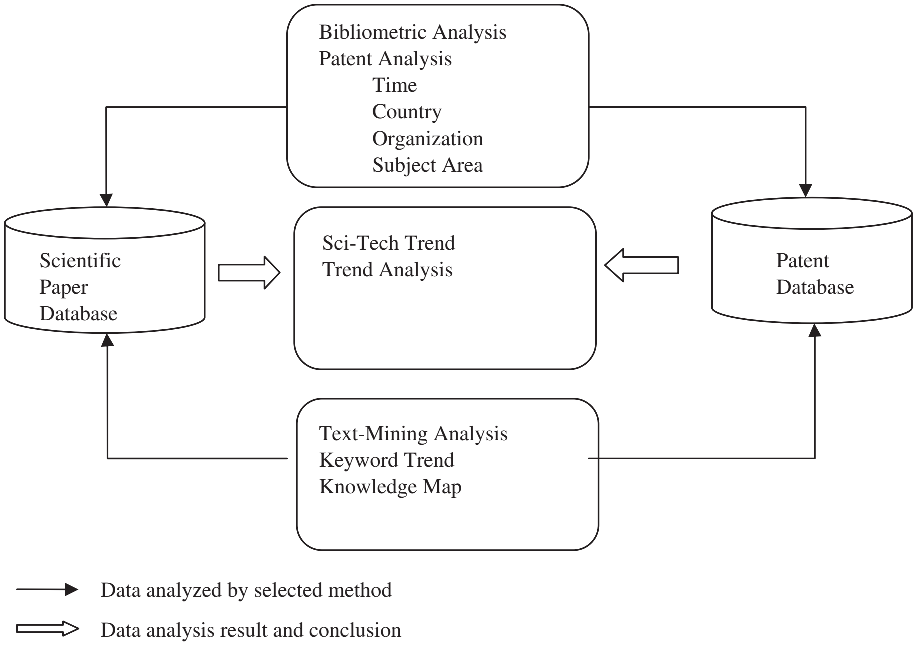

Fig. 4. Research structure.

2.4. Research tool

For bibliometric analysis, this study uses Web of Science [25] webpage to retrieve papers from SCIE. For patent analysis, Delphion [26] is used to retrieve patent information from DWPI. For text-mining analysis, the software developed by Tseng [27] is used in this study.

2.5. Database query strategy

Paper and patent are retrieved by the following query strategy:

1) SCIE: Title = (etch*), Timespan = 1978–2007, Databases = SCI-EXPANDED: a total of 18,481 papers are obtained from SCIE database
2) DWPI: (((etch) <in> TITLETERMS) AND (PD>= 1978-01-01) AND (PD<= 2007-12-31) AND ((US) <in> PN)): a total of 14,102 patents are obtained from DWPI database.

3. Results

Etching is the application of strong acid or physical bombardment to remove unprotected surface area of an object. Two major types of etching are "Wet Etching" and "Dry Etching". Wet etching etches away the objects' surface area by chemical reaction. Dry etching etches away the objects' surface physically by plasma ion bombardment, chemically by plasma free radicals, or the combination of both. As the size of electronic devices gets smaller and smaller in modern electronic products, the performance of etching technology which is usually used in semiconductor industry has become more and more critical in order to obtain high etching uniformity.

To understand the development trend of etching this study applies bibliometric analysis, patent analysis, and text-mining analysis on etching related papers and patents. Results are discussed in the following sections: 1) bibliometric analysis, 2) patent analysis, and 3) text-mining analysis.

3.1. Results: Paper analysis

A total of 18,481 papers were obtained from SCIE database and then analyzed in different dimensions such as time, country, organization, and subject area.

3.1.1. Results: Paper number along time horizon

Fig. 5 shows the number of papers and the growth rate. A steady increase in number of papers can be observed from 1978 to 1996. That there is no obvious increase after 1996 reflects the fast-paced development of etching technology before 1996.

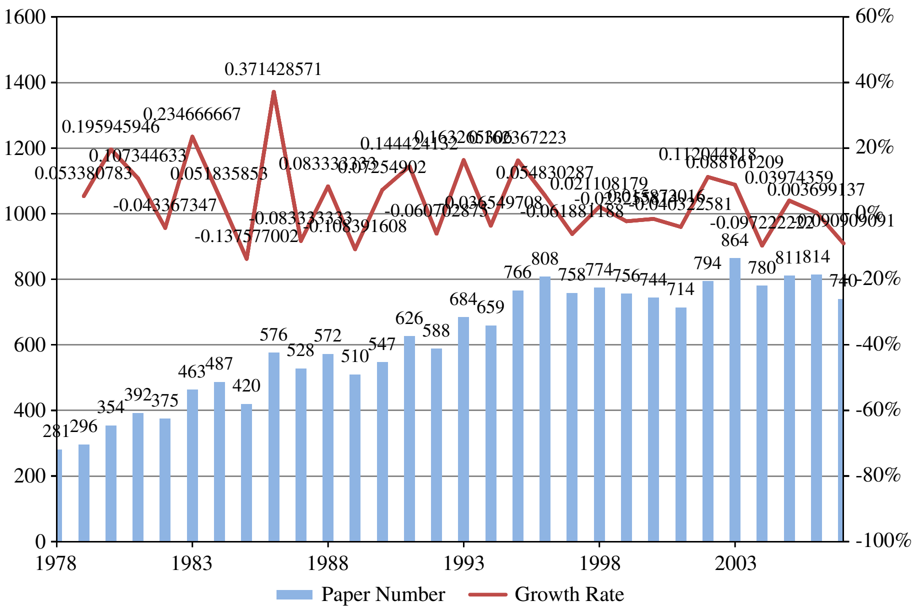

Fig. 5. Paper number and paper growth rate.

The logistic S-curve model is used to fit the trend for the accumulated number of papers, and as shown in Fig. 6, the S-curve model perfectly fits the data with R^2 equal to 0.99992. The fitted curve obtained by the S-curve model indicates that scientific papers in the field of etching follow a conventional growth curve, and thus the "life cycle" of etching papers (which can be regarded as the scientific development of etching) can be studied.

3.1.2. Papers by country

Table 2 shows the number of papers from different countries. The top 10 countries are plotted as a function of time in Fig. 7. The US and Japan are the two countries with the highest amount of papers and these two countries alone published more than 50% of etching papers in the world. This is not surprising because they are traditionally strong in many aspects of research and development. Korea (no. 5), China (no. 7), India (no. 9) and Taiwan (no. 10) are the other four Asian countries in the top 10. This

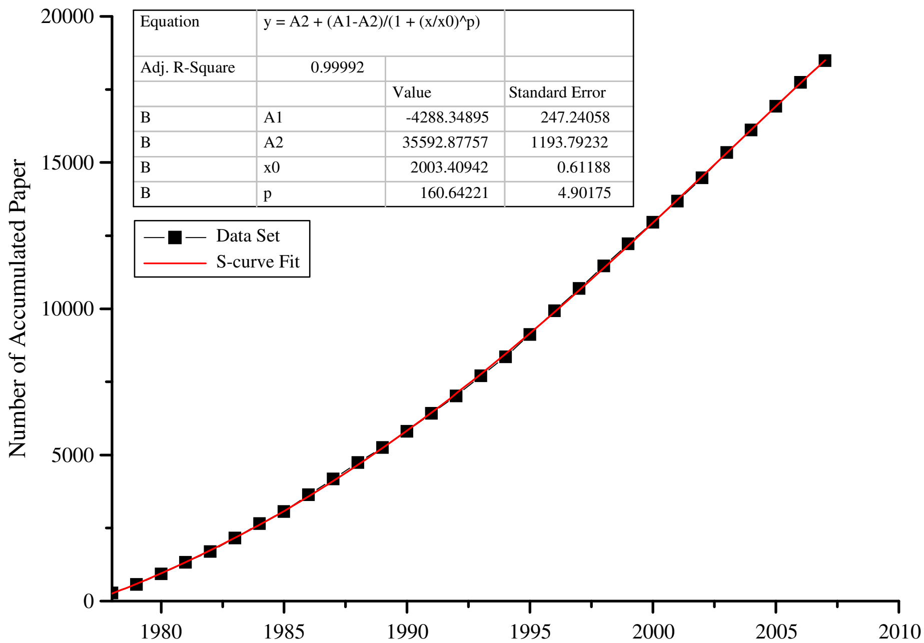

Fig. 6. Accumulated number of papers fitted by the Logistic S-curve model.

Table 2
Top 10 paper numbers by country.

Ranking	Country code	Country	Paper number	%
1	US	USA	6235	33.74
2	JP	Japan	3325	17.99
3	GE	Germany	1145	6.20
4	GB	United Kingdom	1036	5.61
5	KR	South Korea	987	5.34
6	FR	France	847	4.58
7	CN	China	567	3.07
8	NL	Netherlands	447	2.42
9	IN	India	397	2.15
10	TW	Taiwan	376	2.03

indicates very competitive capacity in Asia. Further analysis of the curves shows that after 1998 Korea, China and Taiwan have done aggressive research in this area and lead the rest of the group.

3.1.3. Papers by organizations

Table 3 shows the number of etching papers for different organizations. The number of papers for the top 10 organizations is plotted as a function of time in Fig. 8. Several organizations, such as IBM and AT&T Bell Lab, Sandia National Lab, Nippon Telegraph and Telephone Corporation have reached plateaus without significantly continuous increase after about 1998. MIT, University of Illinois, Osaka University, University of Tokyo, Tohoku University have continuous stable increase after 1998. This shows the difference between university and non-universities. Universities kept publishing etching papers without changing their strategies after 1998.

3.1.4. Papers by subject areas

Table 4 shows the number of etching papers for different subject areas. The number of papers for the top 10 subject area is plotted as a function of time in Fig. 9. The two dominating areas are physics, engineering electrical and electronic. They both combined and account for 60% of all papers. The top 10 subject areas have stable growth rates. After 1993 a significant increase in papers from Nanoscience and Nanotechnology can be observed. This has a lot to do with the popularization of nanotechnology.

3.2. Patent analysis

A total of 14,102 patents have been obtained from DWPI database and then analyzed in different dimensions such as Publication Year, Inventor Country, Derwent Assignee Code, and Derwent Main Class.

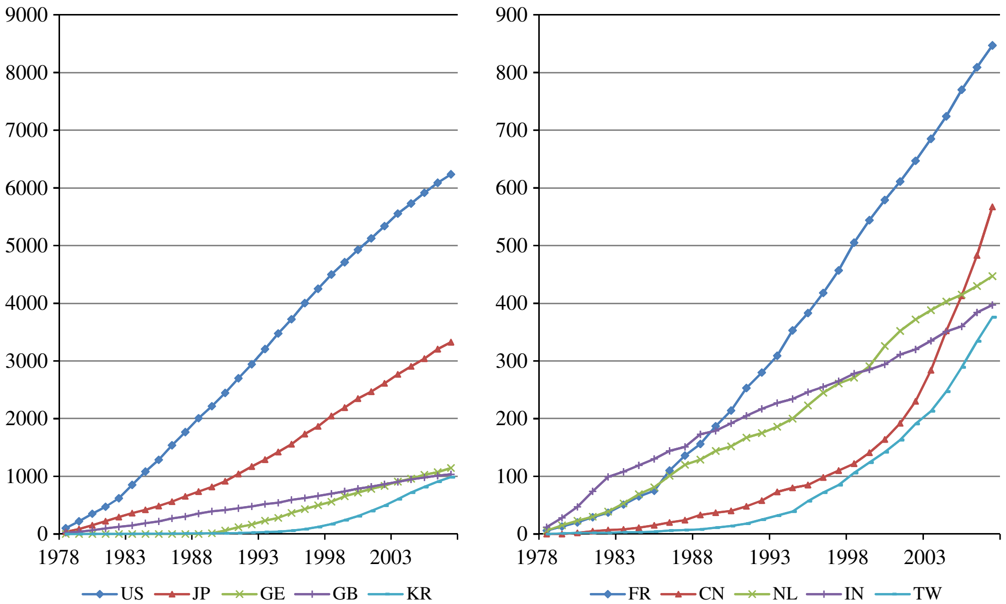

Fig. 7. Top 10 accumulated paper numbers by country between 1978 and 2007.

Table 3
Top 20 paper numbers by organization.

Ranking	Organization code	Organization name	Paper number	%
1	IBMC	IBM CORP	551	2.98
2	AMTT	AT&T BELL LABS	523	2.83
3	FLOR	UNIV FLORIDA	291	1.57
4	MIT	MIT	227	1.23
5	ILLI	UNIV ILLINOIS	194	1.05
6	SAND	SANDIA NATL LABS	189	1.02
7	OSAK	OSAKA UNIV	188	1.02
8	TOKY	UNIV TOKYO	183	0.99
9	NTTP	NIPPON TELEGRAPH and TEL PUBL CORP	173	0.94
10	TOHO	TOHOKU UNIV	167	0.90
11	BERK	UNIV CALIF BERKELEY	156	0.84
12	NEC	NEC CORP LTD	152	0.82
13	HITA	HITACHI LTD	151	0.82
14	CNRS	CNRS	144	0.78
15	RUSS	RUSSIAN ACAD SCI	135	0.73
16	CORN	CORNELL UNIV	133	0.72
17	NAGO	NAGOYA UNIV	132	0.71
18	SUNG	SUNGKYUNKWAN UNIV	130	0.70
19	TEXA	UNIV TEXAS	130	0.70
20	PHIL	PHILIPS RES LABS	125	0.68

3.2.1. Patent number along time horizon

Fig. 10 shows the number of patents and growth rates. A significant growth from 1999 to 2002 is observed.

The logistic S-curve model is used to fit the trend for the accumulated number of patents, and as shown in Fig. 11, the S-curve model is a pretty acceptable model which fits the data with R^2 as high as 0.9917. The obtained S-curve shows that the curve is still undergoing “growth” and suggests that the technology is growing and still has not reached its peak.

3.2.2. Patents by inventor country

Table 5 shows the number of patents in different countries. The sum of Patents from US, Taiwan, Japan and Korea is 96.8%, suggesting that the four countries dominate in etching technology. Taiwan ranked no. 10 in scientific paper performance and ranked no. 2 in patent performance. This has a lot to do with Taiwan's semiconductor industry where etching is one of the primary processes. The higher rankings of Taiwan, Japan and Korea are because of high concentration of electronic industries in these countries.

The number of patents for the top 10 countries is plotted as a function of time in Fig. 12. The US and Canada show a stable increase since 1978, but Taiwan, Japan, Korea, and Singapore show significant increases after 1998–2000. This not only reflects the progress of etching technology in these countries, but also the increased awareness of intellectual property rights in Asia after 1998.

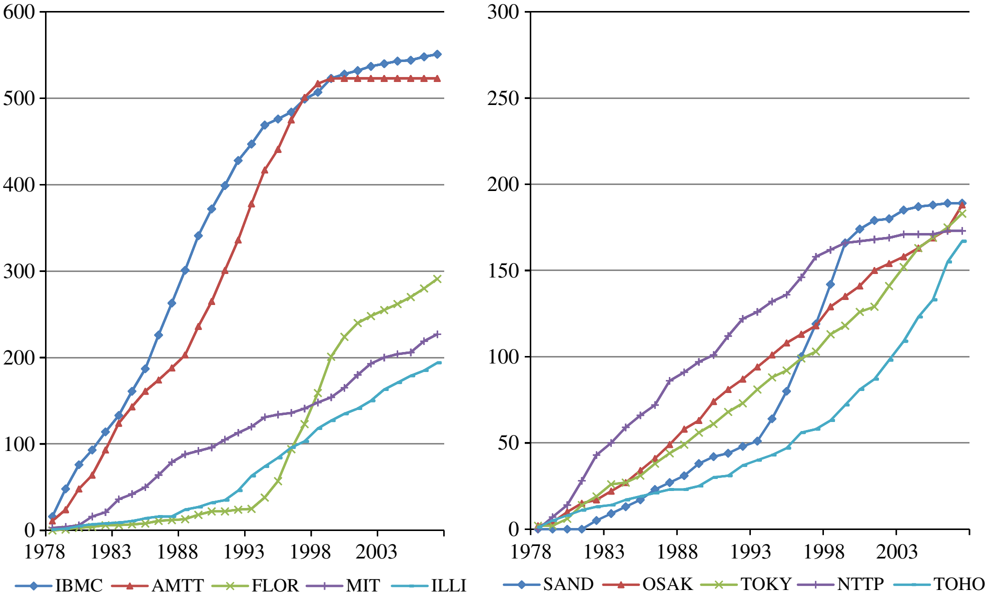

Fig. 8. Top 10 accumulated paper numbers by organization between 1978 and 2007.

Table 4
Top 20 paper numbers by subject area.

Ranking	Subject area code	Subject area name	Paper number	Global percentage (%)
1	PHAP	Physics, applied	7475	40.45
2	ENEE	Engineering, electrical and electronic	3603	19.50
3	MACF	Materials science, coatings and films	3105	16.80
4	MAMU	Materials science, multidisciplinary	2580	13.96
5	PHCM	Physics, condensed matter	1987	10.75
6	NANO	Nanoscience and nanotechnology	1820	9.85
7	ELEC	Electrochemistry	1717	9.29
8	DOSM	Dentistry, oral surgery and medicine	1612	8.72
9	NUCL	Nuclear science and Technology	868	4.70
10	CHPH	Chemistry, physical	848	4.59
11	INST	Instruments and instrumentation	806	4.36
12	OPTI	Optics	779	4.22
13	PHMU	Physics, multidisciplinary	482	2.61
14	CRYS	Crystallography	425	2.30
15	CHMU	chemistry, multidisciplinary	381	2.06
16	MEEN	Metallurgy and metallurgical engineering	345	1.87
17	PAMC	Physics, atomic, molecular and chemical	267	1.44
18	MICR	Microscopy	240	1.30
19	CEBI	Cell biology	224	1.21
20	POLY	Polymer science	205	1.11

3.2.3. Patents by Derwent Assignee Code

Table 6 shows the number of patents for different Derwent Assignee Codes. The top 5 assignees, e.g. Micron Technology, Inc, Taiwan Semiconductor Manufacturing Company, IBM, Samsung and AMD are all electronic and semiconductor related companies. The total patent share of these five companies is 26%, suggesting that most patents are owned by a few large-scaled enterprises.

The number of patents for the top 10 Derwent Assignee Codes is plotted as a function of time in Fig. 13. All the companies show significant increases after 1993, but only the three US companies, IBM, Texas Instruments and Motorola show stable growth from 1978 to 1993.

3.2.4. Patents by Derwent Main Class

Table 7 shows the number of patents for different Derwent Main Classes. The Top two, are: "Electro-(in)organic, Chemical Features of Conductors, Resistors, Magnets, Capacitors and Switches", "Semiconductor Materials and Processes", comprise more than 80% of total patents and are directly related to Semiconductor devices, materials, or processes.

The number of patents for the top 10 Derwent Main Classes is plotted as a function of time in Fig. 14. Most show stable increases and are further triggered after 1998. Those with the steeper growth rates are anticipated to be related to semiconductor or

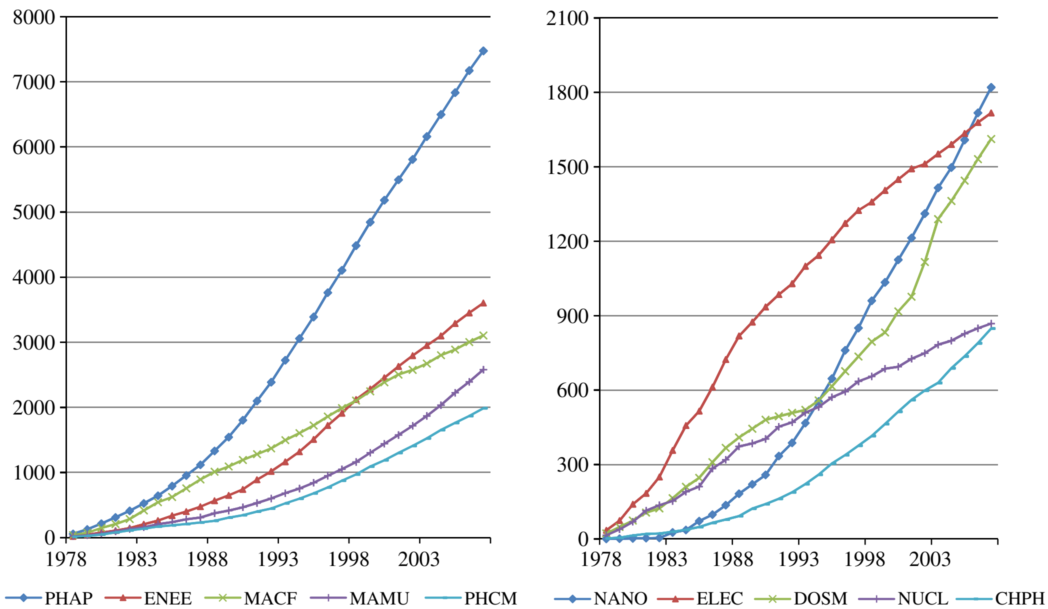

Fig. 9. Top 10 accumulated paper numbers by subject area between 1978 and 2007.

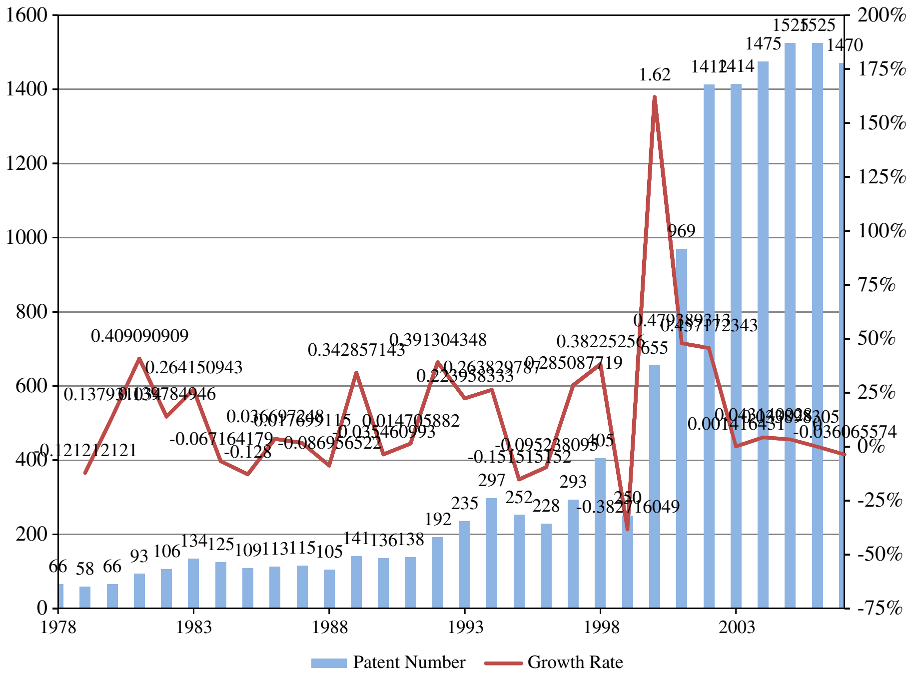

Fig. 10. Patent number and patent growth rate.

electronics, and are confirmed by comparing with Derwent Main Classes descriptions. The two classes where the growth rates are slow are "Decorative Art" and "Other Chemical Surface Treatments".

3.3. Text-mining analysis

Text-mining analysis is conducted by the use of the method developed by Tseng [27] to analyze keyword trends and knowledge maps for both papers and patents. The text-mining methodology specialized for full-text document analysis comprises of four

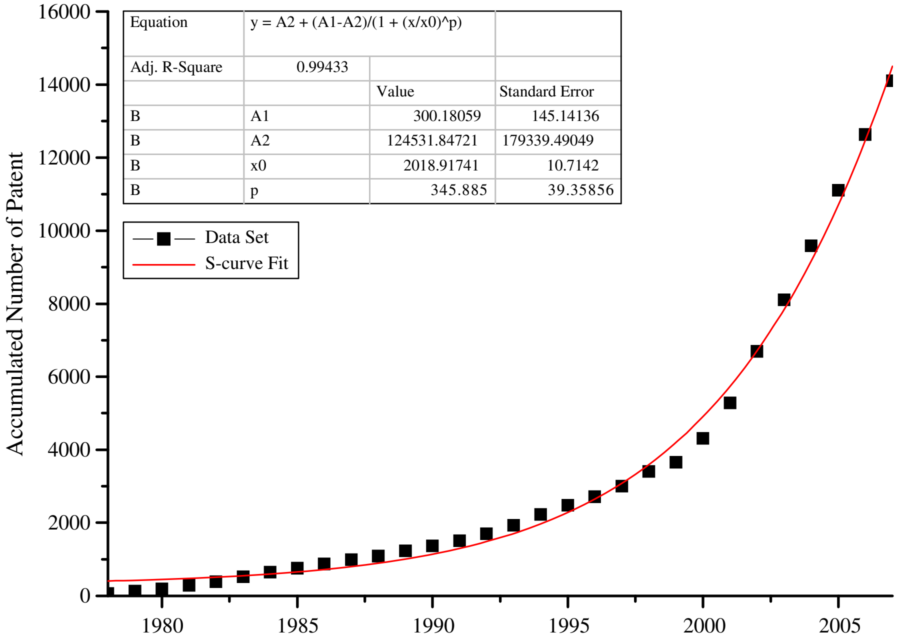

Fig. 11. Accumulated number of patents fitted by the Logistic S-curve model.

Table 5
Top 10 patent numbers by country.

Ranking	Country code	Country	Paper number	Global percentage (%)
1	US	USA	8127	57.63
2	TW	Taiwan	2238	15.87
3	JP	Japan	1702	12.07
4	KR	Republic of Korea	1584	11.23
5	GE	Germany	226	1.60
6	SG	Singapore	224	1.59
7	CA	Canada	70	0.50
8	CN	China	55	0.39
9	FR	France	51	0.36
10	GB	United Kingdom	41	0.29

major steps including Document Preprocessing, Indexing, Topic Clustering, and Topic Mapping. The details of this methodology, such as detailed mechanism, equations, coefficients, etc., were discussed in full by Tseng [27].

3.3.1. Paper text-mining analysis

This study uses the title and abstract of SCIE papers for paper text-mining analysis. The title and the abstract of scientific papers are usually precisely written by the paper authors in order to present the core research results and to communicate with international peers. The obtained paper text-mining results are presented as paper keyword trends and as paper knowledge map in this study.

3.3.1.1. Paper keyword trend. Keywords are extracted from papers and classified by five recent periods of publication years between 1993 and 2007, i.e. 93–95, 96–98, 99–02, 02–04, and 05–07. The frequently used keywords which appear in more than one period are shown in Table 8. The distribution of frequently used keywords in Table 8 provides a dynamic overview of important keywords that represent the core concepts in the scientific development of etching.

3.3.1.2. Taiwan paper knowledge map. From a total of 18,481 papers retrieved in this study there are 376 papers published by Taiwan. The 376 papers are selected to map Taiwan's scientific knowledge of etching by keyword clustering. Keywords that occur more than 50 times are chosen for document clustering analysis. Specifically each document is processed into a vector form such as $d_i = (t_{i1}, t_{i2}, \ldots, t_{im})$, where t_{ij} is the weight of an indexed term j in document i. The effectiveness of clustering relies on (1) how terms are selected; (2) how they are weighted; and (3) how similarities are measured. Based on the experience of topic-based retrieval, among these three factors term selection affects performance most than the other two factors [28].

Table 9 shows the three clusters of important keywords that represent scientific development of etching in Taiwan.

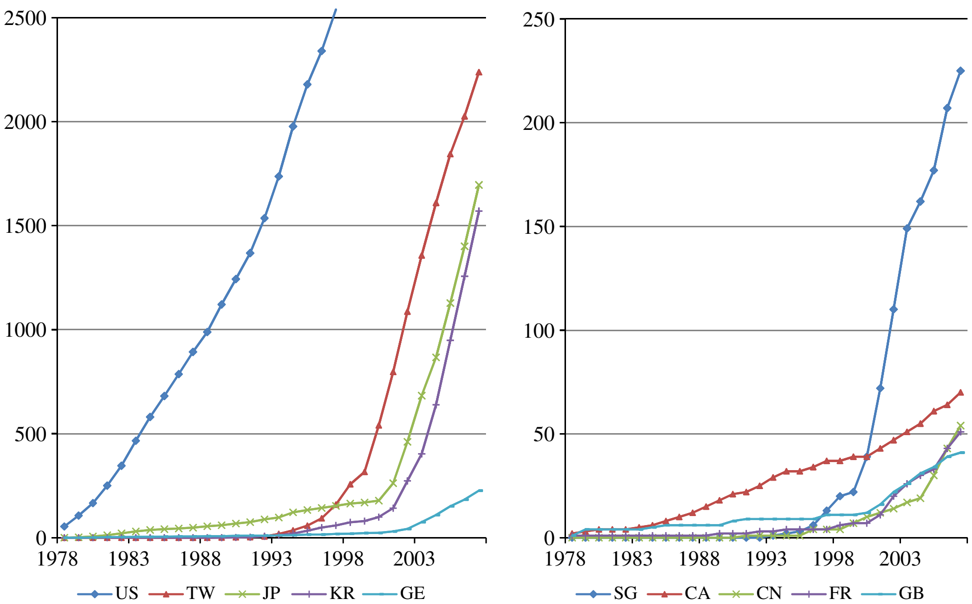

Fig. 12. Top 10 accumulated patent numbers by country between 1978 and 2007.

Table 6
Top 20 patent numbers by assignee.

Ranking	Assignee code	Assignee name	Patent number	Global percentage (%)
1	MICR	MICRON TECHNOLOGY INC	925	6.56
2	TASE	TAIWAN SEMICONDUCTOR MFG CO LTD	788	5.59
3	IBMC	INT BUSINESS MACHINES CORP	786	5.57
4	SMSU	SAMSUNG ELECTRONICS CO LTD	623	4.42
5	ADMI	ADVANCED MICRO DEVICES INC	541	3.84
6	TEXI	TEXAS INSTR INC	399	2.83
7	HYNI	HYNIX SEMICONDUCTOR INC	363	2.57
8	MATE	APPLIED MATERIALS	350	2.48
9	UNMI	UNITED MICROELECTRONICS CORP	327	2.32
10	MOTI	MOTOROLA INC	207	1.47
11	ITLC	INTEL CORP	202	1.43
12	HITA	HITACHI LTD	201	1.43
13	DONG	DONGBU ELECTRONICS CO LTD	195	1.38
14	LAMR	LAM RES CO	187	1.33
15	INFN	INFINEON TECHNOLOGIES AG	172	1.22
16	TKEL	TOKYO ELECTRON LTD	149	1.06
17	CHAR	CHARTERED SEMICONDUCTOR MFG LTD PTE	141	1.00
18	GLDS	LG PHILIPS LCD CO LTD	141	1.00
19	AMTT	AT&T	126	0.89
20	NIDE	NEC CORP	126	0.89

As shown in Fig. 15, frequently used keywords are grouped into several small clusters (circles of different diameters and colors in Fig. 15) and small clusters can be further grouped into three big clusters designated as S120, S085, and S045. The size of a circle is proportional to the number of papers grouped in the same circle. The three big clusters S120, S085 and S045, which represent the significant technology areas in Taiwan are related to dry etching, wet etching, and the mechanism of etching. The three clusters more or less overlap each other. The overlap region is the core of the hot area. Several isolated circles, e.g. 65, 99, 49, 86, 12, 540, and 162, represent some areas loosely connected to the major three clusters.

3.3.2. Patent text-mining analysis

This study uses the title of DWPI patent for patent text-mining analysis. DWPI patent title contains concise, descriptive and English-language sentences. Hence results obtained from text-mining analysis on DWPI patent can be very comprehensive. The obtained patent text-mining results are presented as patent keyword trends and a patent knowledge map in this study.

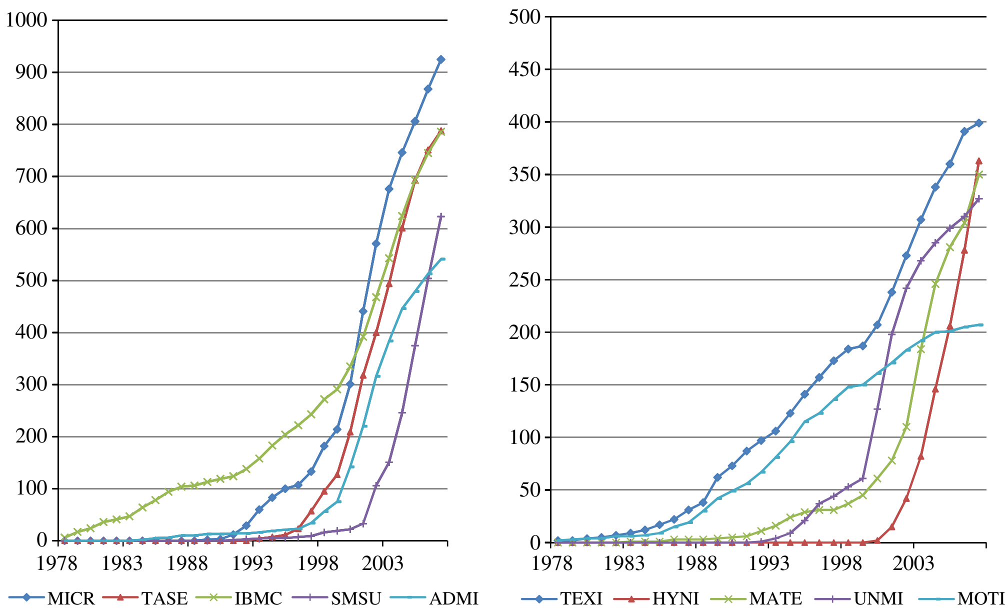

Fig. 13. Top 10 accumulated patent numbers by assignees between 1978 and 2007.

Table 7
Top 20 patent numbers by Derwent Main Class.

Ranking	Derwent Main Class	Description	Patent number	%
1	L03	Electro-(in)organic, chemical features of conductors, resistors, magnets, capacitors and switches	11,456	81.24
2	U11	Semiconductor materials and processes	11,339	80.41
3	U12	Discrete devices	2831	20.08
4	U14	Memories, film and hybrid circuits	2059	14.60
5	V05	Valves, discharge tubes and CRTs	1579	11.20
6	U13	Integrated circuits	1417	10.05
7	P78	Decorative art (B44)	1170	8.30
8	A85	Electrical applications	925	6.56
9	G06	Photosensitive compositions and bases; photographic processes	750	5.32
10	M14	Other chemical surface treatments	544	3.86
11	P84	Other photographic (G03D-H)	538	3.82
12	V04	Printed circuits and connectors	515	3.65
13	P81	Optics (G02)	434	3.08
14	T03	Data recording	385	2.73
15	T01	Digital computers	341	2.42
16	V07	Fibre-optics and light control	329	2.33
17	S03	Scientific instrumentation	328	2.33
18	S02	Engineering Instrumentation.	327	2.32
19	A89	Photographic, laboratory equipment, optical	319	2.26
20	V06	Electromechanical transducers and small machines	291	2.06

3.3.2.1. Patent keyword analysis. Keywords are extracted from patent titles and classified by five recent periods of publication years between 1993 and 2007, i.e. 93–95, 96–98, 99–02, 02–04, and 05–07. Frequently used keywords which appear in more than one period are shown in Table 10. The distribution of frequently used patent keywords in Table 10 provides a dynamic overview of important keywords that represent the core concepts in the technological development of etching.

3.3.2.2. Taiwan patent knowledge map. From 14,102 patents obtained in this study 2238 of them were from Taiwan. These 2238 patents are selected to map Taiwan's technological knowledge of etching by keyword clustering. Keywords that occur more than 50 times are chosen for clustering analysis. Table 11 shows the five clusters of important patent keywords that represent the technological development of etching in Taiwan.

As shown in Fig. 16, frequently used keywords are grouped into several small clusters (circles of different diameters and colors in Fig. 16) and small clusters can be further grouped into five big clusters designated as D640, D450, D679, D564, and D164. The size of a circle is proportional to the number of papers grouped in the circle. The two biggest clusters D450 and D640 are defined by black dashed line in Fig. 16. D450 as the largest cluster (1054 patents, 47%) comprises eight smaller circles which are pretty close to each other, suggesting a specific focus for Taiwan's etching patents.

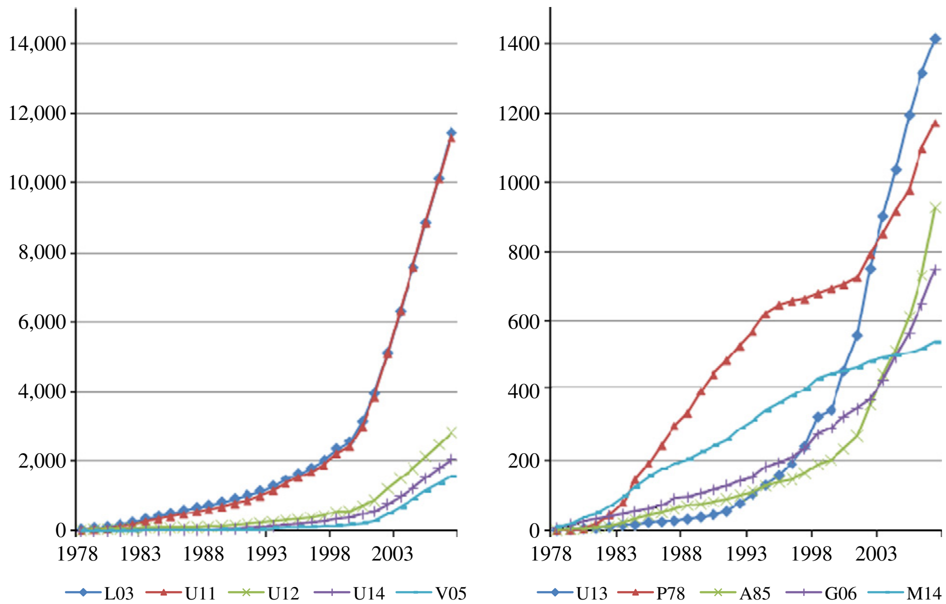

Fig. 14. Top 10 accumulated patent numbers by Derwent Main Class between 1978 and 2007.

Table 8
Paper keyword trend.

Keywords	93–95	96–98	99–01	02–04	05–07
Etch rate, plasma, structure, silicon, surface, ion, dentin, rate, reactive	■	■	■	■	■
Film, chemical, bond		■	■	■	■
Layer, density			■	■	■
Solution	■	■		■	■
Microscopy		■		■	■
RIE	■			■	■
Pattern, porou, bond strength, adhesive, self-etching, electrochemical				■	■
Dry		■	■		■
Inductive coupl, clean, degree			■		■
Model, fabricate, wet etch, cell, optical, diamond, deposition		■			■
Track	■				■
Beam	■	■	■	■	
Damage, gas			■	■	
Growth	■	■		■	
Oxide, anisotropic, primer, electron		■		■	
Detector, resin	■			■	
Gaa	■	■	■		
Gate		■	■		
Enamel	■		■		
Pit, wire, concentration, membrane	■	■			

■ : Keyword appears in the time period.

4. Findings

According to the above results obtained by analyzing SCIE papers and DWPI patents from several perspectives, eleven findings can be discussed in two dimensions: 1) Sci–Tech development: findings on the scientific and technological development of etching, and 2) Trend analysis method: findings on trend analysis method applied on this case study.

4.1. Finding 1)

Sci–Tech Development: (a) SCIE paper numbers reach the maximum in 1996 and DWPI patent numbers reach the maximum in 2005 (b) Regression model curve fitting shows that SCIE papers have reached the “mature stage” but DWPI patents are still in the “growing stage”.

Trend Analysis Method: By analyzing the number of papers and patents, it can be observed that science begins earlier than technology in a life cycle.

Table 9
Taiwan's paper keywords.

Cluster code	Number of paper	Keyword
S120	155	Surface, plasma, film, gas, damage
S085	80	GaN, wet etch, KOH, fabricate, n-type
S045	52	Acid, surface, solution, electrode, oxide

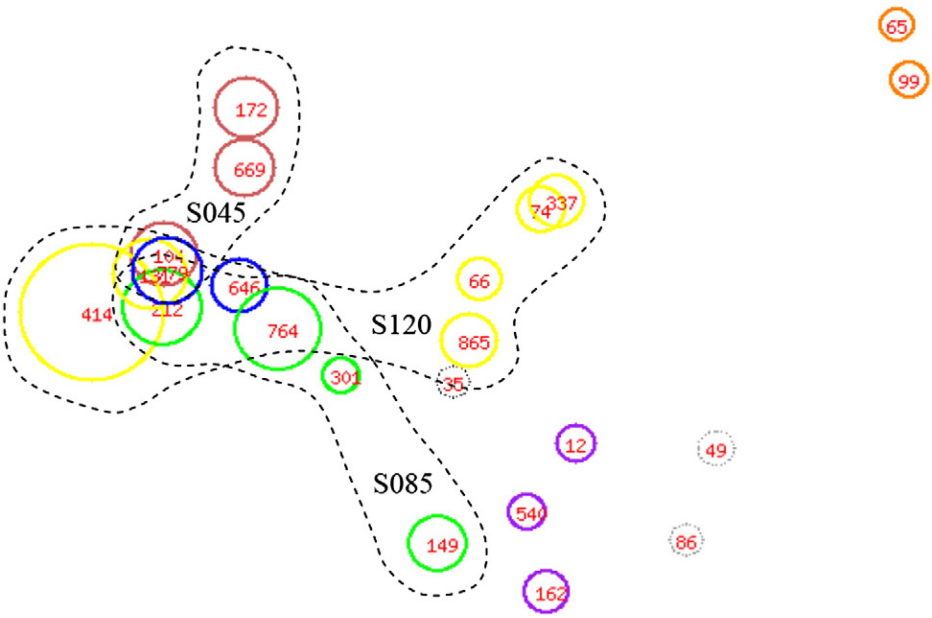

Fig. 15. Taiwan paper knowledge map.

Fig. 17 shows SCIE paper numbers and DWPI patent numbers along a time horizon. SCIE paper reaches maximum in 1996 and DWPI patent number reaches maximum in 2005. According to Martino's stage of innovation [1], innovation diffusion is a process where knowledge diffuses from basic science research to applied technology development. SCIE papers can be regarded as the carrier of basic science research and DWPI patents can be seen as the carrier of technology development (Fig. 2). The stage of

Table 10
Patent keyword trend.

Keywords	93–95	96–98	99–01	02–04	05–07
Layer, surface, device, semiconductor, dielectric, metal	■	■	■	■	■
Mask		■	■	■	■
Pattern, semiconductor device, circuit, plasma, wafer	■		■	■	■
Gate, involve, ion			■	■	■
Film	■			■	■
Magnetic, epitaxial, array				■	■
Manufacture, trench			■		■
Electrode		■			■
Acid	■				■
Substrate	■	■	■	■	
Silicon, capacitor		■	■	■	
Photoresist, reactive, oxide			■	■	
Copper, gas	■			■	
Etchant	■	■	■		
Cell, contact		■	■		
Integrate, formation, material	■		■		

■ : Keyword appears in the time period.

Table 11
Taiwan's patent keywords.

Cluster code	Number of patent	Keyword
D450	1054	Oxide, mask, memory, semiconductor, gate
D679	132	Involve, dielectric, metal, open, trench
D640	263	Circuit, open, device, fabrication, involve
D564	161	Pattern, photoresist, substrate, device, structure
D164	56	Wafer, gas, surface, portion, plasma

innovation indicates that the mature time of science should occur earlier than that of technology development, and the result of SCIE papers and DWPI patents supports this theory of "stage of innovation".

By looking at the results of regression model analysis, the S-curve fit for SCIE papers (Fig. 6) has almost reached the maximum of the fitted curve but DWPI patents are still growing continuously (Fig. 11). This again supports the observation that science (papers) had matured but technology (patents) is still growing. The regression model analysis shows that scientific papers come earlier than patents and therefore support the theory of technology life cycle.

4.2. Finding 2)

Sci–Tech Development: The semiconductor industry is in its business cycle recovery stage which leads to significant increase of patent numbers in 2001 and 2002.

Trend Analysis Method: Market demands come earlier than patent growth.

According to Derwent Main Class, about 80% DWPI patents are semiconductor related. The Derwent Assignee Code shows that the six assignees, i.e. MICRON TECHNOLOGY INC, TAIWAN SEMICONDUCTOR MFG CO LTD, ADVANCED MICRO DEVICES INC, TEXAS INSTR INC, INTEL CORP, APPLIED MATERIALS, INFINEON TECHNOLOGIES AG, are about one third of the 19 semiconductor companies of the Philadelphia Semiconductor Index (SOX) which is the most heavily traded index on the Philadelphia Stock Exchange. Therefore we speculate that semiconductor business cycle is related with industrial R&D.

SOX is compared with paper and patent numbers as shown in Fig. 18. SOX jumps from 200 in October 1998 to 1200 in March 2000, a six-fold growth. This is consistent with the significant jump of patents from 250 patents in 1999 to 1412 patents in 2002, which is also about six times. Therefore, it can be concluded that business cycle influences industrial R&D and market demand leads patent growth, even though more evidence is desirable to consolidate this finding.

4.3. Finding 3)

Sci–Tech Development: Paper and patent numbers are relatively more similar in the US, Japan, Korea, Singapore than Taiwan, Germany, UK, and France. The similarity between paper numbers and patent numbers implies a "symmetrical" development between science and technology. Taiwan is the only country that has more patents than papers.

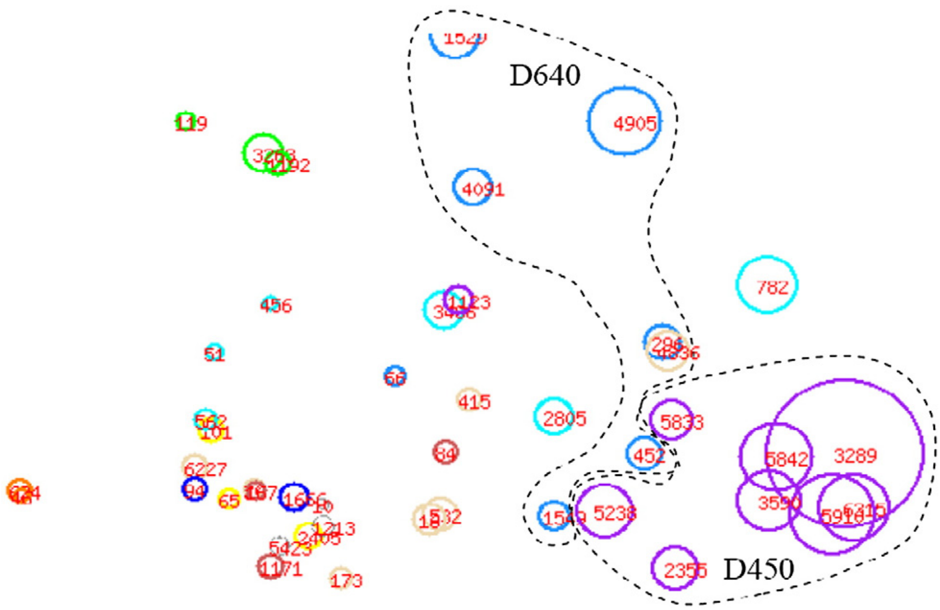

Fig. 16. Taiwan patent knowledge map.

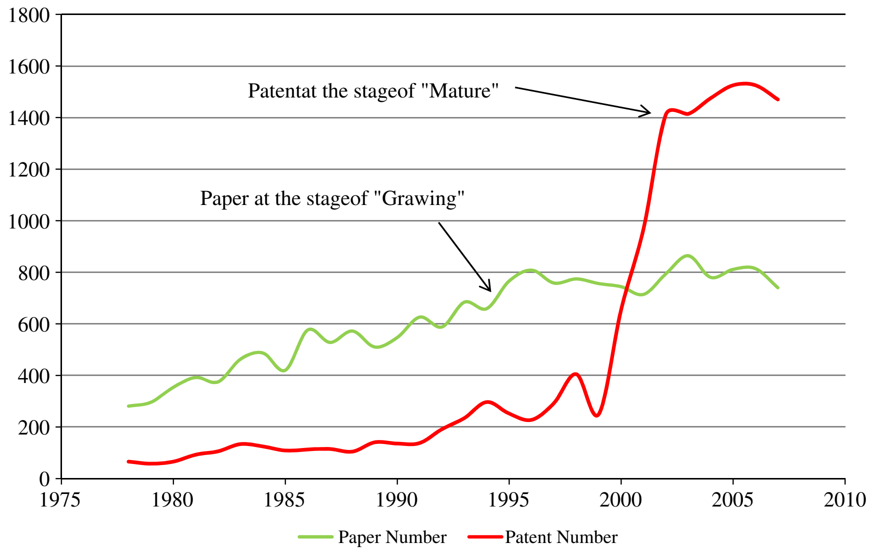

Fig. 17. The number of paper and patent between 1975 and 2007.

Trend Analysis Method: Comparison between the number of papers and patents in each country allows an understanding of the strength of the linkage between government and enterprise in a country.

Fig. 19 shows patent numbers vs. paper numbers. Countries located at the diagonal line are those where paper numbers are similar to patent numbers, i.e. the US, Japan, Korea, and Singapore. The countries that have large difference between patent numbers and paper numbers are UK, Germany, France, China, Canada, and Taiwan and located away from the diagonal line on the graph. The discrepancy between paper numbers and patent numbers might imply inefficient interaction between academy and industry or a poor linkage between governments and enterprises. Lin and Lin [29] argue that poor interaction between academy and industry causes the problem of inefficient conversion from government R&D funding to industrial productivity. The observation is supported by Taiwan's case from where we find that papers are barely cited by patents [29].

4.4. Finding 4)

Sci–Tech Development: IBM and AT&T produced a great number of papers and patents before 1993.

Trend Analysis Method: Organizational analysis shows that big enterprises are R&D leaders and thus have large number of papers and patents.

Figs. 8 and 13 show that IBM and AT&T initiated etching technology and acted as R&D leaders. However, AT&T did not have paper or patent output after 2000, because in 1996 AT&T spun off Bell Labs, along with most of its equipment-manufacturing

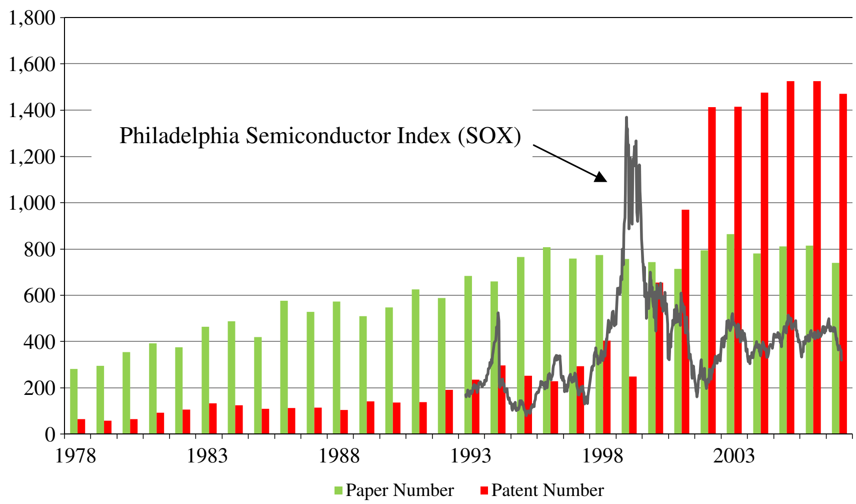

Fig. 18. Philadelphia Semiconductor Index and number of paper and patent between 1978 and 2007.

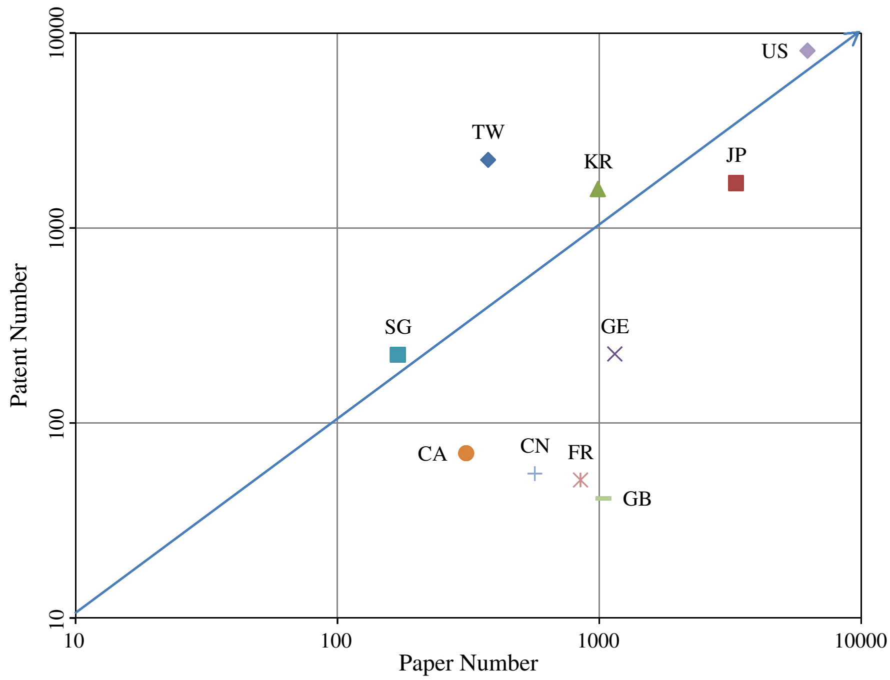

Fig. 19. Paper number vs. patent number for selected country.

business, into a new company named Lucent Technologies. IBM has also slowed down its etching R&D and gradually has transformed into a technology service company due to manufacturing cost/competitive pressures and an emphasis on systems, software, and services.

4.5. Finding 5)

Sci–Tech Development: (a) France, Russia, Korea, and the Netherlands are countries that have papers concentrated on major research institutes, (b) Taiwan, Korea, Germany, and Singapore are countries that have patents concentrated on major assignees, (c) Korea has the highest concentration in both papers and patents where most papers and patents are owned by several big research institutes and companies.

Trend Analysis Method: The number of research institutes and assignees that own papers or patents reflects the policy of R&D allocation in a country.

Table 12 shows national percentages of paper or patent numbers for top 20 (global ranking of paper or patent) organizations. Global ranking is based on global patent or paper numbers.

For those Asian countries and the US listed in Table 12 are:

1. Paper: Korea (no of organization: 1, total national percentage: 13.20%), Japan (no of organization: 7, total national percentage: 34.50%), US (no of organization: 9, national percentage: 38.30%).
2. Patent: Singapore (no of assignee: 1, total national percentage: 76.10%), Korea (no of assignee: 4, total national percentage: 82.60%), Taiwan (no of assignee: 1, total national percentage: 32.50%), Japan (no of assignee: 3, total national percentage: 28.00%), US (no of assignee: 11, national percentage: 60.50%).

Singapore has the highest uneven distribution on patent because INFINEON TECHNOLOGIES has 76.1% of total patents owned by Singapore. Taiwan also has pretty high patent concentration due to TAIWAN SEMICONDUCTOR MFG CO LTD which has 35.2% of total patents owned by Taiwan. Although this may suggest their uneven distribution of etching technologies, we believe that it makes more sense to interpret the phenomenon as strategic technological allocation for a small country like Singapore.

Uneven distribution is also observed in Korea where few research organizations and companies own a very large portion of papers (no of organization: 1, total national percentage: 13.20%) and patents (no of assignee: 4, total national percentage: 82.60%). This indicates that Korea strategically allocates R&D resources to a small number of big organizations. Different levels of distribution reflect different strategies of R&D allocation. Taiwan which is very similar to Korea in very many aspects has patent and paper distributions more uneven than Korea and relies heavily on TAIWAN SEMICONDUCTOR to have outstanding patent performance.

Table 12
National percentages of paper or patent number for top 20 (global ranking of paper or patent) organizations.

Global ranking	Paper		Patent	
	Organization name	National percentage (%)	Assignee name	National percentage (%)
1	IBM CORP	8.8	MICRON TECHNOLOGY INC	11.4
2	AT&T BELL LABS	8.4	TAIWAN SEMICONDUCTOR MFG CO LTD	35.2
3	UNIV FLORIDA	4.7	INT BUSINESS MACHINES CORP	9.7
4	MIT	3.6	SAMSUNG ELECTRONICS CO LTD	39.3
5	UNIV ILLINOIS	3.1	ADVANCED MICRO DEVICES INC	6.7
6	SANDIA NATL LABS	3.0	TEXAS INSTR INC	4.9
7	OSAKA UNIV	5.7	HYNIX SEMICONDUCTOR INC	22.9
8	UNIV TOKYO	5.5	APPLIED MATERIALS	4.3
9	NIPPON TELEGRAPH and TEL PUBL CORP	5.2	UNITED MICROELECTRONICS CORP	14.6
10	TOHOKU UNIV	5.0	MOTOROLA INC	2.5
11	UNIV CALIF BERKELEY	2.5	INTEL CORP	2.5
12	NEC CORP LTD	4.6	HITACHI LTD	11.8
13	HITACHI LTD	4.5	DONGBU ELECTRONICS CO LTD	11.5
14	CNRS	17.0	LAM RES CO	2.3
15	RUSSIAN ACAD SCI	41.5	INFINEON TECHNOLOGIES AG	76.1
16	CORNELL UNIV	2.1	TOKYO ELECTRON LTD	8.8
17	NAGOYA UNIV	4.0	CHARTERED SEMICONDUCTOR MFG LTD PTE	62.9
18	SUNGKYUNKWAN UNIV	13.2	LG PHILIPS LCD CO LTD	8.9
19	UNIV TEXAS	2.1	AT&T	1.6
20	PHILIPS RES LABS	28.0	NEC CORP	7.4

4.6. Finding 6)

Sci–Tech Development: Taiwan's paper knowledge map shows that paper knowledge is more widely distributed than patent knowledge.

Trend Analysis Method: Paper and patent knowledge maps show both similarity and dissimilarity of knowledge. The distribution of knowledge is objective evidence that can serve as a basis for allocating R&D resources.

The comparisons between the paper knowledge map (Fig. 15) and the patent knowledge map (Fig. 16) show relatively wider knowledge distribution in the paper knowledge map and more focused in the patent knowledge map. Often free academic research is not as strategically conducted as inventions of patented technologies. This is confirmed in Taiwan's paper knowledge map and patent knowledge map. The higher knowledge concentration on patent knowledge map suggests that a large number of R&D resources have been invested in similar fields and therefore previous inventions can possibly be infringed by new inventions. Paper and patent knowledge maps provide useful tools for evaluating R&D resource allocation as well as prevention of IPR infringement.

5. Discussion and conclusion

5.1. Trend analysis method

According to the research framework proposed in Fig 3, trend analysis is pursued from macroscopic investigation (bibliometric analysis) to microscopic investigation (text-mining analysis), and from theory (scientific papers) to application (patents), in order to have a full-spectrum understanding on development trends in different dimensions. This creates six relationships to be explored.

Six relationships in the research framework:

1) *Bibliometric/Patent analysis and paper database*: Conventional bibliometric/patent analysis that is usually used on evaluating scientific output from governments, universities, and research institutes.
2) *Bibliometric/Patent and patent database*: Bibliometric/patent analysis method on patent is usually used on understanding technological performance of research institutes or companies.
3) *Text-mining and paper database*: Clustering of papers by co-keyword method and identification of important keywords in each cluster to uncover emergent research areas from papers. Text-mining on paper database aims to identify emerging scientific research areas.
4) *Text-mining and patent database*: Clustering of patents by co-keyword method and identification of important keywords in each cluster to uncover emerging research areas from patents. Text-mining on patent database aims to identify emerging technological development.
5) *Bibliometric/patent and text-mining*: Bibliometric/patent analysis is a macroscopic statistic created by the use of paper or patent metadata, but text-mining is a microscopic statistic created by the use of keywords in each paper or patent.

6) *Paper database and patent database*: Papers are the most important carrier of scientific knowledge and patents are the most important carrier of technological knowledge, both are different in nature. In a series of innovative processes, the causal relation existing between papers (scientific research) and patents (technological development) is globally recognized.

For a sound trend analysis method, bibliometric analysis should be conducted first to understand an overview of both science and technology development. This should be followed by discovering emerging research areas microscopically. Both paper and patent databases should be used as data sources for balanced understanding of science and technology.

5.2. Innovation diffusion

1) Scientific development and market demand are initial indicators of the life cycle of patented technology.

From research findings 1): bibliometric analysis shows that the life cycle of fundamental research begins earlier than technology development, and from research findings 2): market demand begins earlier than patent numbers' growth. Both the scientific push and the market demand pull lead the patented technology life cycle. Combining this with Martino's theory—patent as a leading indicator, the interactions among scientific development, market demands, patent number and market share can be illustrated as Fig. 20.

Fig. 20 shows that continuous scientific development pushes patent numbers growth and technology commercialization. The increase of market share also induces R&D preferences in companies which tend to invest more resources on expanding market share. Martino argues that there is a gap between scientific development and commercialization and it takes 4–6 years of innovation diffusion to cross the gap. Interactions between scientific development and market demand have also been investigated; for example, 1) Market demand pull: Frame et al. found that the coal gasification literature has experienced explosive growth trebling in size between 1972 and 1974, and some of this growth may be associated with the energy crisis caused by Arab Oil Embargo of 1973–1974 [30] and 2) Scientific development push: The discovery of interferon therapy in cancer brought significant impact on expansion of biotechnology market [31].

2) Scientific development accelerates commercialization of technology, and market demand pulls innovation diffusion.

According to Martino's stage of innovation basic research comes earlier than technology development. Knowledge diffuses from basic scientific research to technology development if techniques involved become more and more mature. Research findings show insignificant influence of market demand to paper numbers, but market demand has a stronger impact on patent numbers. Hence market demand pulls the diffusion of innovation.

Continuous scientific development offers a theoretical foundation for technological application. For example, scientific breakthroughs may reduce manufacturing cost and therefore accelerate filing patents to protect the IPR of inventions based on the scientific breakthroughs. However, this study finds that market demand pull has a stronger impact on patent numbers than does technology push, which suggests a demand driven innovation.

5.3. Etching development trend

1) Science of etching is now in the "mature" stage of its life cycle, but technology of etching is in the "growth" stage. The need for smaller-sized and highly efficient electronic products will encourage future commercialization of more advanced etching technologies.

The S-curve model, used for fitting paper numbers along a time horizon (Fig. 6), shows a pretty nice fit; hence, we predict that paper numbers have reached the upper limit and therefore the "mature" stage for scientific papers can be suggested. The S-curve model is also a reasonable fit for patent numbers (Fig. 11), but the patent numbers are still increasing as a function of time; so, we suggest that patents are at the "growth" stage. The change in patent numbers in the most recent three years shows that it will gradually step into the "mature" stage.

Etching in the last thirty years has been analyzed in this study. Significant progress in both science and technology is observed. The trend of lighter, smaller, highly efficient electronic product encourages minimization of gate line-width in Integrated Circuit;

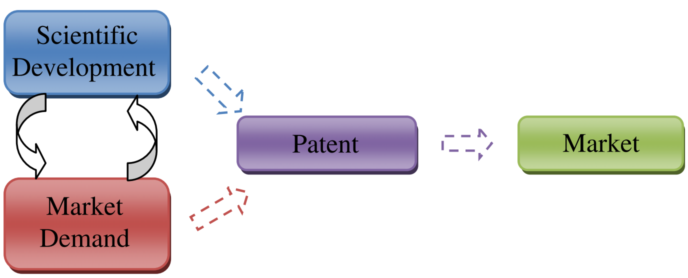

Fig. 20. Relations between scientific development, market demand, patent and market share.

thus more devices can be integrated on a single chip. A continuous Sci–Tech development on etching in the future can be forecasted.

2) Global leaders of etching have shifted from US based companies to Asian companies, particularly South Korean semiconductor companies. Taiwan's TSMC and UMC have established great bases for technology development in etching, but there is still room to improve in Taiwan, in terms of basic research and industry–academy collaboration.

IBM and AT&T initiated etching technology in the 1980s. The modern semiconductor industry that utilizes etching technology has changed from an integrated device manufacturing (IDM) business model to a contract manufacturing business model integrating upper stream—IC design, middle stream—wafer manufacturing, and lower stream—IC packaging and testing. The whole semiconductor industry has also expanded from the US, Japan, and German to Taiwan, South Korea, and Singapore. This study shows Samsung Electronics and Hynix Semiconductor are very active in the technological development of etching in the last three years. Some of the active technological developments of Samsung Electronics and Hynix Semiconductor may be associated with the recent collaboration between the two companies. They have forged an alliance to develop spin torque transfer magnetic RAM (STT-MRAM), to help Korea maintain its global leadership in the microchip market and to take the global initiative in developing next-generation chips [32].

Taiwan's patent numbers are only second to the US, and Taiwan's patented techniques are dominated by TSMC and UMC. However, Taiwan's paper numbers are only ranked no. 10 and are far from satisfactory. For Taiwanese research organizations with etching papers, National Chiao Tung University is ranked no. 55 (56 papers), National Tsing Hua University is no. 65 (50 papers), National Cheng Kung University is no. 69 (48 papers), and the others are ranked out of the top 100. Compared to the US, Japan, Germany, and South Korea which are top countries in both paper and patent numbers, Taiwan's unsatisfactory paper performance indicates inefficient interaction between industry and the academy, and invested government research funding is not converted to industrial application for national competitiveness. Advancement of Sci–Tech policy to sort out such problems in Taiwan is necessary.

6. Suggestion

6.1. Suggestion for etching

1) The integration of patent analysis and paper analysis is desirable to allow industry to understand scientific advancement and allow the academy to understand technological application. A longer term R&D planning is therefore possible for industry and the academy.
2) Text-mining analysis shortens the time required for reviewing a large amount of literature. Text-mining analysis allows the possibility of instantly monitoring Sci–Tech development.
3) Etching technology is still in the “growth” stage. Samsung Electronics and Hynix Semiconductor are Taiwan's competitors in the semiconductor industry.
4) Taiwan should enhance interaction between industry and the academy.

6.2. Suggestion for future research

1) Analysis of other technologies by the use of the integrated method proposed in this study is necessary, in order to understand the technology development context affected by national policy, industrial ecology, and the global economic environment.
2) Citation or co-citation analysis can also be used in bibliometric analysis to uncover more hidden information.
3) Other databases can also be used and then the analysis results compared, e.g. paper databases (Engineering Index, Scopus, etc.) and patent databases (EPO, JPO, USPTO, Triadic Patents, etc.).
4) Other commercial text-mining software can be used for comparison, e.g. VantagePoint, Thomson Data Analyzer, STN AnaVist, etc.
5) Investigation on relationships between patents and papers through some methodologies, e.g. a) patent's citation to paper, b) paper's citation to patent, c) co-occurrence of sub-topic, organization, or inventor/author on both patent and paper. These can be analyzed to unveil the paper–patent relationship.

7. Contribution

7.1. Contribution to the academy

1) This study proposes an integrated method and systematic research framework to analyze Sci–Tech development trend to supplement research methods that solely use paper or patent databases.
2) Trend analysis should be studied from macroscopic investigation (bibliometric analysis) to microscopic investigation (text-mining analysis) and from theory (scientific papers) to application (patents) in order to have a full-spectrum understanding on development trends in different dimensions.
3) This study confirms that scientific development and market demand are the leading indicators for patented technology life cycles.
4) Scientific development accelerates commercialization of technology and market demand pulls innovation diffusion.

7.2. Contribution to industry

1) Science of etching is now at the "mature" stage in its life cycle, but technology of etching is at the "growth" stage. The need for smaller-sized and highly efficient electronic product will always encourage future commercialization of more advanced etching technologies.
2) Global leaders of etching technology have shifted from US based companies to Asian companies, particularly South Korean semiconductor companies. Taiwan's TSMC and UMC have established great bases for technology development in etching, but there is still room to improve in basic research and industry–academy collaboration.

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