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Bibliometric trend analysis on global graphene research

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Abstract Graphene is a rising star as one of the promising materials with many applications. Its global literature increased fast in recent years. In this work, bibliometric analysis and knowledge visualization technology were applied to evaluate global scientific production and developing trend of graphene research. The data were collected from 1991 to 2010 from the Science Citation Index database, Conference Proceeding Citation Index database and Derwent Innovation Index database integrated by Thomson Reuters. The published papers from different subjects, journals, authors, countries and keywords distributed in several aspects of research topics proved that graphene research increased rapidly over past 20 years and boosted in recent 5 years. The distinctions in knowledge map show that the clusters distributed regularly in keywords of applied patents in recent 5 years due to the potential applications of graphene research gradually found. The analytical results provided several key findings of bibliometrics trend.

Keywords Graphene · Bibliometric analysis · Research trend · Co-words · Co-authorship · Knowledge mapping

Introduction

Graphene, the latest single-layer two-dimensional (2-D) material, attracts many researchers from material science to condensed-matter physics for its unusual electronic, mechanical,

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and thermal properties. Graphene is composed of a single layer of carbon atoms, which densely packed into a benzene-ring structure. Originated from 1947 theoretically (Wallace 1947), planar graphene had been presumed not to exist in free state, being unstable due to the formation of curved structures such as soot, fullerenes, and nanotubes (Odegard et al. 2002). With the constant discovery of carbon-based materials, including graphite, large fullerenes, nanotubes, this 2-D material aroused attention of scientists. Up to now, a lot of papers have been published, and many papers and patents reported new findings. Graphene technology was selected as one of the top ten emerging technologies by Massachusetts Institute of Technology (MIT) in 2008 (Bullis 2009), one of the top ten scientific advances of 2009 selected by *Science* magazine (Science 2009), and awarded Nobel Physics Prize in 2010 (Nobelprize 2010).

In graphene research, sample preparation was the most difficult problem and had been solved eventually by Andre K. Geim and Novoselov K.S in 2004. They found an easy and effective way of micromechanical cleavage (Novoselov et al. 2004). The publications of grapheme research then broke out, and the properties, applications as well as the studies of this single atomic plane of graphite attracted attentions of researchers all over the world. A great number of academic conferences were hold for graphene research, and more and more consortiums and governments in the world began to support the research activities (Ciraci et al. 2004) of this material because of its abnormal properties such as band structure, quasiparticles in it formally identical to massless, chiral fermions (Zhang et al. 2005). This newly found one-atom-thick material distinguished from other carbon-based materials. The productions, publications and related studies on graphene developed rapidly. As a result, the patents on graphene increased rapidly after 2007. The application will be extended and new technologies will be developed in coming years.

According to previous studies, the preparation approaches of graphene can be summed up as a physical method of extracting a single sheet by micromechanical cleavage from graphite (Novoselov et al. 2005), a crystal method of stowing layers of atoms (Hass et al. 2008) by Multilayer Epitaxial Graphene (MEG), a chemical method of depositing single layer of carbon atoms (Wilk et al. 2001) by Chemical Vapor Deposition (CVD) or a chemical deoxidizing method from the materials of graphite oxide or graphene oxide. The research of graphene characterization employed a few advanced technologies such as Atomic Force Microscopy (AFM), Transmission Electron Microscope (TEM), Scanning Electron Microscope (SEM), Optical Microscope (OM), X-ray Diffraction (XRD), and Raman Spectrum (RS). This single-atom-layer material deserves good examination for its excellent physical and chemical properties (Sen et al. 2010). It is likely that more different methods will be developed to prepare graphene in near future. As a result, the research papers on graphene sample preparation will be the majority of the publications.

Property study is also important of this new substance. In fact some kind of unusual physical properties called quasiparticles (Katsnelson et al. 2006) have attracted scientists to study the electronic effect of graphene. Because of its 2-D structure, graphene has quite different electronic transaction properties (Geim and Novoselov 2007) compared to common substance, therefore the findings of this new planner carbon material provide much chance for physicists to understand or to learn the phenomenon of Chiral Quantum Hall Effects (McCann and Fal'ko 2006) and Dirac-Fermions (Novoselov et al. 2005) on modern physics. The extension of graphene structure can also open many physical research fields for scientists. Through carefully investigation, it was found that the physical properties study is the main field of the graphene research. Compared to physical properties the study of its chemical properties was left behind, which could be another field need to pay more attention. Present chemical studies focus on the surface properties (Chen, Chen et al. 2007). The internal structure has not been discovered yet and should be studied finely. The reaction between graphene and other chemical substance could also bring scientists new research directions. We can expect that the studies of unknown chemical or thermal properties will bring many research output in this area.

Graphene is a promising material to be explored in future. As this paper stated, graphene can be used in the field of electronic device for its extraordinary conductivity (Berger et al. 2006), mechanical application for its higher intensity far more than steel (Tung et al. 2009). It can be also used as the carrier of cell device in energy material (Standley et al. 2008), bio-sensor in biology field (Cappelli et al. 2005) potentially and even the computer manufacturing (Ilyin et al. 2010) soon. The output of such research will bring us great benefits in the next decade. It is invaluable to concern the development of its production.

In recent years, scientometrics has been used as quantitative analysis method for scientific research. The derived statistics that measuring the contribution of scientific publications within a given topic (Su and Lee 2010) could represent current research trends and be used to identify focuses of future. Through bibliometric research of literature, the next research trend could be predicted (Garfield 1970). In this study, we analyzed the papers as well as patents of graphene research productivity in its short history. The discussion described global scientific production including SCI, CPCI papers and DII patents on graphene research from following aspects:

- Growth of global publication output and patent production from 1991.
- Distribution of subject categories of research productivity.
- Journals of publication identified.
- Countries of publication and international collaboration analysis.
- Citation analysis of research publications.
- Authorship and coauthorship of papers.
- Distribution of author keywords and co-words analysis.

The records of literature were analyzed with bibliometric methods via several aspects. This effort will provide a current view of the mainstream research on graphene all over the world, as well as clues to the impact of this hot topic. In addition, this study also attempted to analyze the significance of the 2-D graphene production patterns, especially in the way of coauthors and authors' keywords study originally acted from SCI database. The main body of this article includes scientometric analyses in document type, subject category, and publication distribution of SCI and DII data. Also patterns of authors, countries/regions, institutes, and journals (Fernandez-Canon et al. 2002; Enachescu and Postelnicu 2003; Faba-Perez et al. 2003). Moreover, appropriate statistical tests were used in the authors' keyword yearly to predict the developing trend of graphene research.

Data collection and research methodology

Data source

The data were retrieved on December 31st, 2010 from Science Citation Index (SCI), Conference Proceeding Citation Index (CPCI) and Derwent Innovation Index (DII) database offered by the producer by Thomson Reuters, which were operated by Thomson Scientific, Philadelphia, PA, USA (Chen, Chen et al. 2007). The retrieval strategy were arranged as topic = graphen* or single layer graphit* (* = wildcard including the plural) with all years timespan within WoS. It was found that before the term graphene created, single layer graphite was used to stand for graphene for quite a long time. So the single layer graphite was used as another important retrieval word.

As a strictly selected abstract database, Web of Science (WoS, including SCI and CPCI) has been long recognized as the most authoritative scientific and technical literature indexing tool that can provide the most important areas of science and technology research (Boyack et al. 2005). From the period of 1991–2010 there were 8,727 graphene related research papers in SCI that distributed in several document types, and 1,121 papers from CPCI. The impact factor (IF) of SCI journals in 2009 was determined by Journal Citation Reports (JCR) of ISI, which was the latest data available.

SCI citation search system is unique, not only from the perspective of literature cited but also from the academic assessment of the value on articles or network research references. Citation counts of the top papers are based on the SCI data at the date of searching on December 31st, 2010.

According to international patent records retrieved from 2001 to now, more than 50 countries applied 823 patents distributed in 15 subjects to protect core technology on graphene of their own. Since the patent authority lagged from application for years, the patents data in the graph imaged the facts of research productivities before.

Bibliometric methods

In this bibliometric study, the publications, subjects, collaborations, times cited, co-words, cluster analysis of the papers and patents were deeply examined. The Thomson Data Analyzer (TDA) and Aureka software were employed to analyze the papers as well as patents data for knowledge mapping.

It is called co-author when multi-writers appeared simultaneously in one paper, this reflects the collaboration of different institutes, regions or countries (Cooper 2003). The higher the strength is, the closer the relationship among them. Collaboration between countries was determined by the author description, where 'independent' was assigned if no collaboration presented. International collaboration was assigned if it was co-signed with researchers from more than one country. Co-words means the phenomenon that two or more keywords occur simultaneously in one article of that field, the times of which is called the frequency or strength of co-words (Leydesdorff 1997). In this study, co-author and co-word analysis were used to analyze the collaboration among several research organizations through visualization technology.

Results and discussion

In this part, figures and tables were used to describe the production and the future trends of graphene research. Publications (as indicator for scientific performance) and patents (as indicator for technological performance) are commonly accepted indicators for quantitative innovation research (Rajagopal 2002). Papers from SCI, CPCI as well as patents from DII were studied separately using bibliometric analysis.

SCI papers analysis

Global publication output

The publication output of graphene research from 1991 to 2010 is shown in Fig. 1. During the passed decades SCI papers on grapheme research produced from five in 1991 to more than 2000 after 2009. The annual number of publication growing exponentially from 2005, indicating that the research had aroused more and more attention recently.

The document type was listed in Table 1. For the ones covered more than ten papers, which are considered to guide the reader. There are 7,523 articles, which comprised 86.20% of the total 8,727 SCI production, followed by proceedings papers (626; 7.17%), reviews (198; 2.27%), news items (171; 1.95%), Editorial Material (78; 0.89%), corrections (75; 0.86%) and other document types were neglected.

Languages of all articles in this study were grouped. English is the main language of papers on grapheme publications. Several other languages such as Chinese, French, German, Russian, Spanish, and Japanese also appeared. English remains the dominant language as it is the main language in many fields. It could be expected that a higher percentage of English would be used because most journals listed in ISI are published in English (Chiu and Ho 2007).

Subject categories of research productivity

Based on the classification of subject categories in Journal Citation Report (JCR) of ISI, the publication output data of graphene research was distributed in 75 subject categories

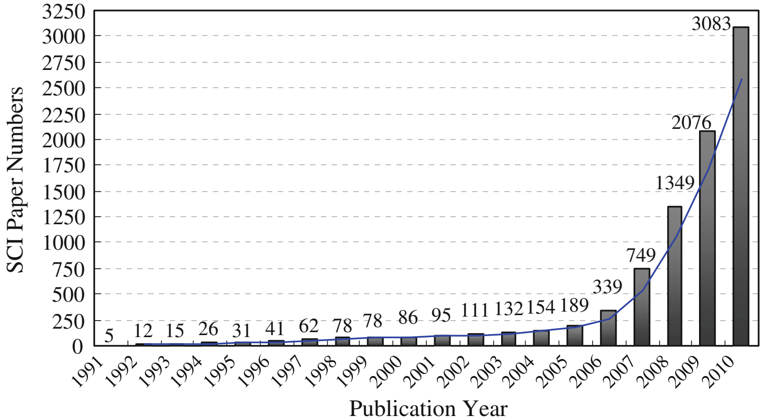

Fig. 1 SCI papers published from 1991 to 2010

Table 1 Document types of SCI papers

Document type	Article	Proceedings paper	Review	News item	Editorial material	Correction	Letter	Meeting abstract
Records	7523	626	198	171	78	75	33	13
Rate (%)	86.20	7.17	2.27	1.95	0.89	0.86	0.37	0.15

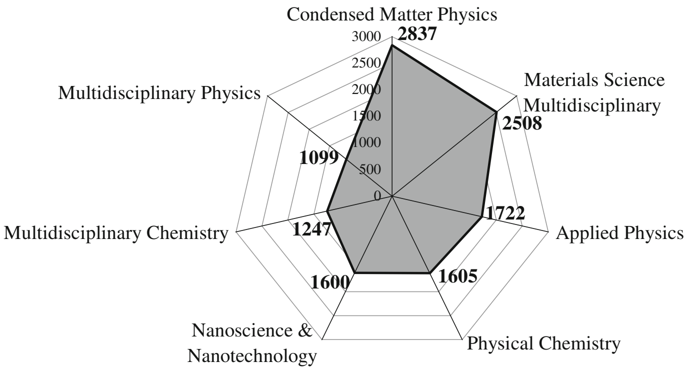

Fig. 2 Main subjects of SCI papers on graphene

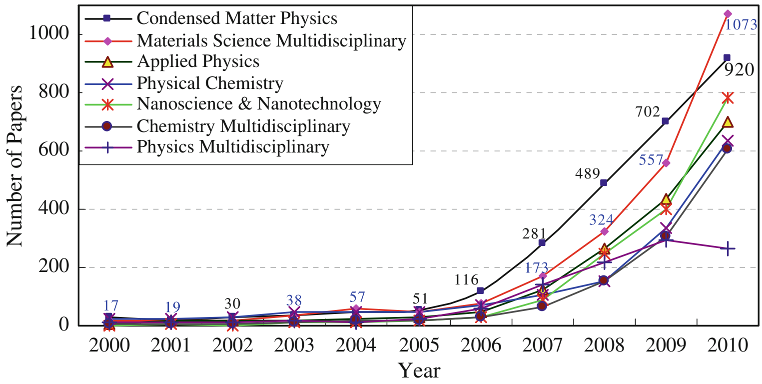

Fig. 3 Annual subjects distribution of SCI papers

during the last two decades. Subject categories containing at least 1,000 articles are shown in Fig. 2. These seven most productive subjects were all branches of physical science and produced 84% of graphene publications.

Figure 2 shows that the graphene research mainly distributed in the fields of condensed matter physics, materials science and applied physics. The preparation and property research tend to physical aspect since it has been found. Moreover, present studies use more and more approaches on physics. The Physics Nobel Prize 2010 honored to the graphene research for its deep exploring on the physical properties.

From Fig. 3, it can be seen that the graphene research locate in the subject of condensed matter physics for a long time before 2009, so the study of graphene was considered as one branch of physics fields. In fact, graphene is more a kind of interesting material instead, and the property research of it focused on magnetic, electrical, chemical and other field. Therefore, the curve in red showed that materials science related subject will be the mainstream of graphene research in future.

Journals of publication

In JCR 2009, 7387 journals are listed in the SCI, 402 journals of it were about the subject of physics. The graphene research output was published on 382 journals and the ones with

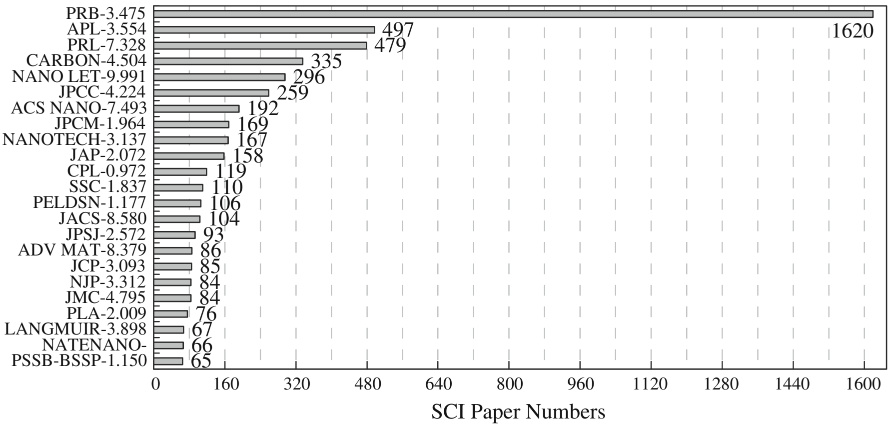

Fig. 4 Top productive journals with its IF

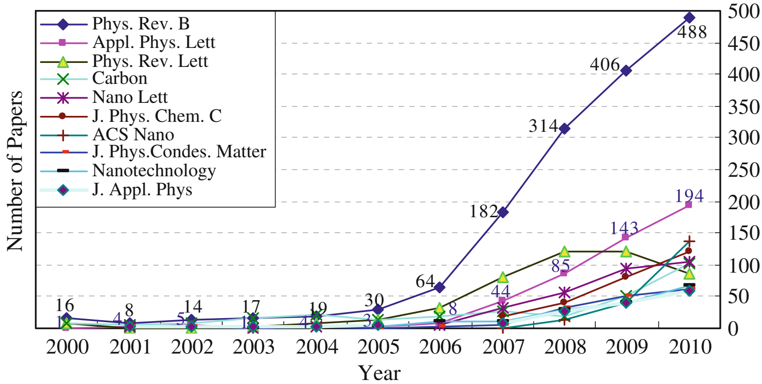

Fig. 5 Annual journals distribution of SCI papers

more than 50 articles are displayed in Fig. 4. Approximately 30% SCI papers were reside in these top three most productive journals, which are *Physics Review B* (PRB, 1620), *Applied Physics Letter* (APL, 479) and *Physicas Review Letter* (PRL, 497), with the impact factors (IF) of 3.475, 3.554, 7.328, respectively. Whereas the remainders resided in others took a less ratio than that.

PRB covered 43% of the graphene research papers in 2005 and this ratio increased after that. From Fig. 5 it can be also seen that APL published articles rose from 3 to 194 during this period. However, the graphene publications in PRL dropped dramatically during 2006–2010. Publication of other journals increased little but steadily in these years. From the analysis it can be expected that PRB will still be the primary journal for the graphene research publication in coming period.

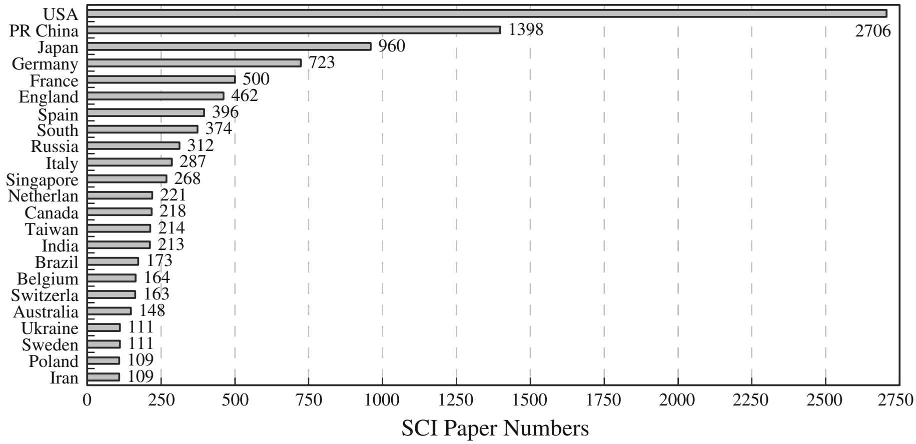

Fig. 6 Top countries with SCI papers published

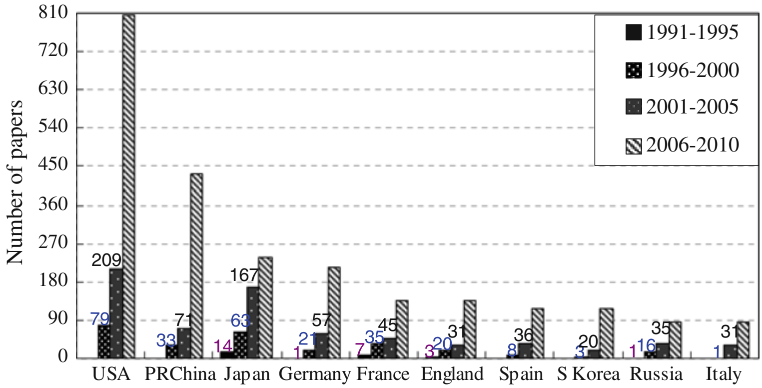

Fig. 7 SCI publications distribution of countries in different period

Country of publication and International collaboration

The output of SCI articles on graphene from different countries are presented in Fig. 6. The most active country was USA with about one quarter of all publications. SCI publications from P.R China, Japan, Germany and France were 1398, 960, 723 and 500, respectively. Japan was the third active country according to the total papers published, but its proceeding was more than that of China (see Fig. 14). It can be inferred that Japan preferred international communications and collaborations. The top productive countries carried out most international collaboration with others in the grapgene research.

Figure 7 shows the published papers of the top ten productive countries during four different periods (the bar of USA was one-third scaled down for better visualization). It can be concluded that graphene research started in most countries during 1996–2000, and boosted after 2006. Japan, France and England began their graphene research before 1996 and kept a steady increasing during the four time periods. Compared to China, Japan started early but dropped behind in SCI paper numbers in near decades, USA was the leading country during last decade with a dramatic increase on papers published, its number increased from 79 to 2418 during 1991–2010.

Citation analysis of research publications

The total citation count obtained from SCI showed the total times that a particular article cited by other research work listed in the SCI database. The number of citations does not necessarily indicate the quality of a paper, but it is a measure of its impact and/or visibility in this field. The most frequently cited articles (>1000 times) of each year in 1991–2010 were selected (see Table 2). The most frequently cited one was "Electric field effect in atomically thin carbon films" in 2004 by Novoselov KS et al. It has been cited 3,522 times since it was published. Meanwhile, Novoselov KS and Geim AK at the University

Table 2 Top SCI papers cited more than 1000 times

No.	Time cited	Authors	Title	Institute	Country	Year
1	3522	Novoselov KS, Geim AK, Morozov SV	Electric field effect in atomically thin carbon films	Univ Manchester	England	2004
2	3192	Thess A, Lee R, Nikolaev P	Crystalline ropes of metallic carbon nanotubes	Rice Quantum Inst	USA	1996
3	2649	Novoselov KS, Geim AK, Morozov SV	Two-dimensional gas of massless dirac fermions in graphene	Manchester Ctr Mesosci & Nanotechnol	England	2005
4	2429	Geim AK, Novoselov KS	The rise of graphene	Manchester Ctr Mesosci & Nanotechnol	England	2007
5	2307	Zhang YB, Tan YW, Stormer HL	Experimental observation of the quantum Hall effect and Berry's phase in graphene	Columbia Univ	USA	2005
6	1943	Hu JT, Odom TW, Lieber CM	Chemistry and physics in one dimension: synthesis and properties of nanowires and nanotubes	Harvard Univ	USA	1999
7	1422	Saito R, Ujita M, Resselhaus G	Electronic-structure of chiral graphene tubules	MIT	USA	1992
8	1382	Rao AM, Richter E, Bandow S	Diameter-selective Raman scattering from vibrational modes in carbon nanotubes	Univ Kentucky	USA	1997
9	1287	Odom TW, Huang JL, Kim P	Atomic structure and electronic properties of single-walled carbon nanotubes	Harvard Univ	USA	1998
10	1214	Castro Neto AH, Guinea F, Peres NMR	The electronic properties of graphene	Boston Univ	USA	2009
11	1084	Berger C, Song ZM, Li XB	Electronic confinement and coherence in patterned epitaxial graphene	Georgia Ins Technol	USA	2006
12	1038	Rinzler AG, Hafner JH, Nikolaev P	Unraveling nanotubes-field-emission from an atomic wire	Rice Univ	USA	1995

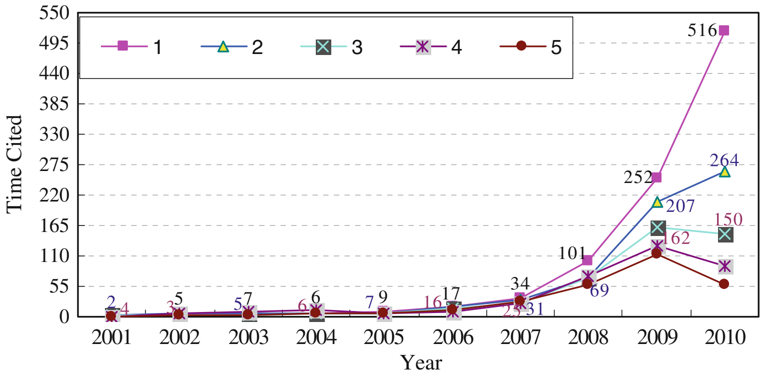

Fig. 8 Annual cited times distribution of SCI papers

Manchester contributed the highest number (No. 1, 3 and 4) of articles among the 12 most frequently cited articles, which exhibited their predominance.

The most frequently cited articles prove that researchers from the world concentrated their attention to the electron and physical properties of graphene. From this it can be concluded that the graphene research trend will focus on their natural properties. These top cited papers were completed all by scientists from the institutes in developed countries. At the same time papers on other research fields of graphene were cited rarely. From Fig. 8, it can be concluded that 1–5 times cited papers increased main since 2007, but high frequently cited papers increased few and in the future it may increase as we can expect.

Authorship and co-authorship of papers

As shown in Fig. 9, most work on the graphene research was done by 2–4 researchers, especially by three scientists, which is the mainstream of all research activity. Meanwhile some of the graphene studies were the results of the collaboration by more than three authors. This collaboration kind between scientists or their institutes is the trend of modern research activity.

Most graphene research was done by the collaboration of several scientists. It can be seen from Fig. 9 that the three scientist term increased most rapidly after 2006, two or four person terms increased not as steady as that of three or five authors. Convenient modern communications make the collaborations possible. Single author articles increased from 2005 to 2009 in linear expansion, however, it didn't increased as fast as papers published by few co-authors. The analysis indicates that collaboration is possible and necessary for the graphene research.

On the other hand, collaboration between one or two organizations is 76% as shown in Table 3. Collaboration with authors from more than three institutes is in the minority, which covered lees than one quarter. From this date, it can be concluded that the collaboration between more than two institutes is not as convenient as one or two organizations do. In the model of collaboration, the first author come from one research organization and the second author maybe in the same organization or not (13:12), but the third one is likely not from the other research organization (3:1).

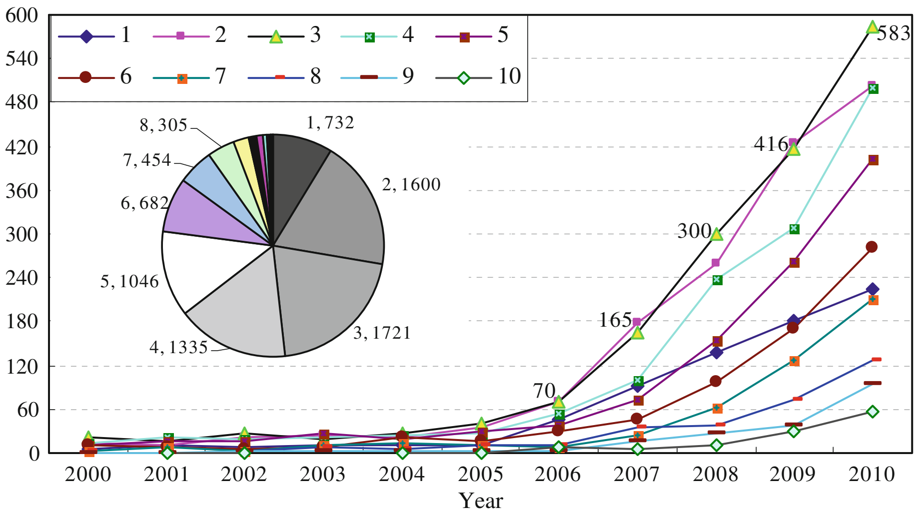

Fig. 9 Annual number of authors of SCI papers published

Table 3 The institutes distribution of SCI papers

Author affiliations number	1	2	3	4	0	5	6	7	8	10
SCI records	3456	3166	1168	431	325	124	39	14	3	1
Rate (%)	39.60	36.27	13.38	4.93	3.72	1.42	0.45	0.17	0.04	0.01

Distribution of author keywords and co-words

The technique of statistical analysis of keywords and title-words may indicate directions of research. Especially, authors' keywords analysis could offer the information of research trends as viewed by researchers (Garfield 1970). The examination of authors' keywords in this study showed that 5,625 author keywords were used from 1991 to 2010. Table 4 listed the seven most used author keywords with their rankings and percentages, and other low frequently keywords were neglected.

As shown in Fig. 10 most frequently used author keywords distributed in 4 year periods. Except "graphene" was the searching word in this study, the two most frequently used author keywords were "carbon nanotubes" and "graphite". "Carbon" and "Nanostructured materials" were also the most popular author keywords in the past 20 years, and both of them have high increasing rates in recent years. During the past 5 years the keyword

Table 4 Keywords records of SCI Papers

Authors' keywords	Graphene	Carbon nanotubes	Graphite	Carbon	Nanostructured materials	Density functional theory/nanotubes	Electronic structure/Raman spectroscopy
Records of SCI	3330	3033	1123	413	300	118	38
Rate (%)	39.86	36.30	13.44	4.94	3.59	1.41	0.46

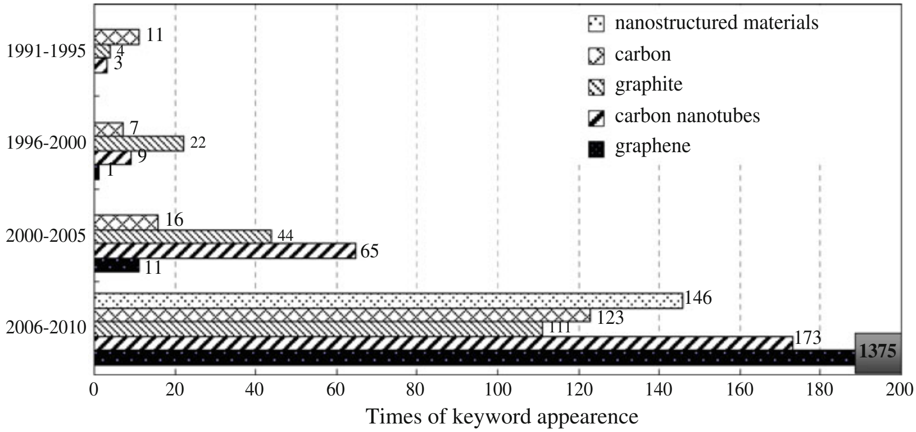

Fig. 10 Times of keywords in different period, 1991–2010

"graphene" totally conducted the research topics. In addition, "carbon nanotubes" and "nanostructured materials" were also the new emerging keywords in the graphene related research. The extremely high increasing rate in the ranking of author keywords such as the relevant "graphite" or "carbon" showed the importance of them and made them be the next new focus.

CPCI paper analysis

Conference thesis comprised the front of the rapidly open reports about scientific research or discovery, through which people can learn the new progress in their research field rapidly. So CPCI database conveyed lots of important and latest research information.

Global publication output

It can be seen from Fig. 11 that not many researchers pay their attention to the graphene research before 1995 and only a few papers published and few proceedings reported the progress of related work. During 1996–2004 some scientists began their research work on graphene, several progresses about this single carbon atom layer material had been reported. After the preparation method of graphene been found in 2004, the number of proceedings boomed rapidly and diploid upraised steadily.

Since 2006, the conference "International Graphene Week" was held yearly by some research societies. Germany held the first conference in September, 2006. Then Graphene 2008 in August at Italy; Graphene 2009 in March at Obergurgl of Austin; Graphene 2010 in April at Maryland of USA and Grapehene Brazil 2010 in December at Belo Horizonte, Minas Gerais, Brazil. In the same time KITP Miniprogram: Electronic Properties of Graphene was hold in June 2007 by UC of USA; Graphene Canada 2008 was held in September by albert Banff of Canada; Graphene Tokyo 2009 was held in July by Tokyo of Japan; Computational Physic and Chemistry of Graphene in October by Losong of Swaziland; and International Meeting on the Chemistry of nanotubes and Graphene was held in April by Arcachon of France. All these conferences contributed a lot to CPCI data after 2006.

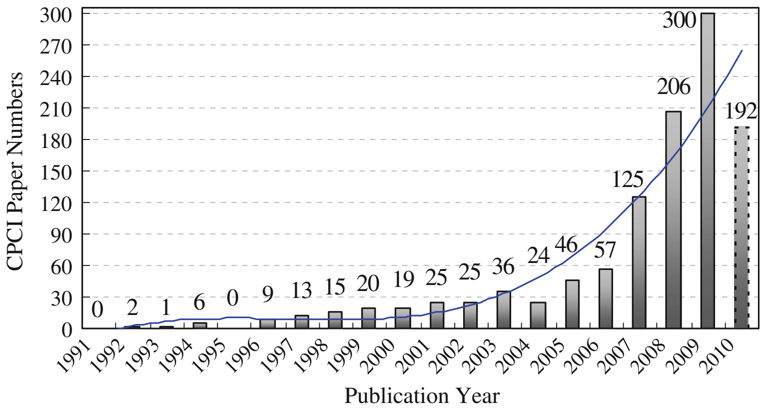

Fig. 11 CPCI papers published from 1991 to 2010

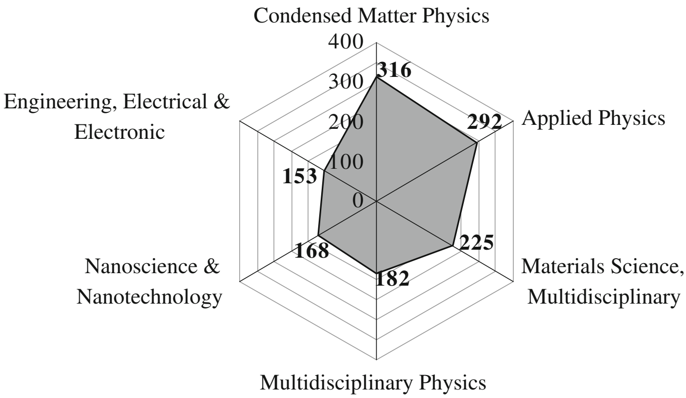

Fig. 12 Main subjects of CPCI papers

Subject categories of research productivity

The subjects of papers from CPCI database were less distinctively focused on the materials science than SCI data. Nevertheless, physics related subjects were the main domain of the graphene reports, and nanoscience and nanotechnology of graphene attracted less researchers' attention so that the literature production took up relatively weak portion in the CPCI data. The engineering, electrical & electronic are the new emerging subjects in CPCI papers, as shown in Fig. 12.

Subjects in condensed physics and applied physics covered the most papers from annual proceedings. Figure 13 shows that materials science subject increased slowly during 2000–2009. After 2003, the graphene subject on engineering, electrical & electronic increased rapidly while nano related subjects decreased in 2009. The physics, electronics as well as engineering will be the future hot topics in the graphere related conferences.

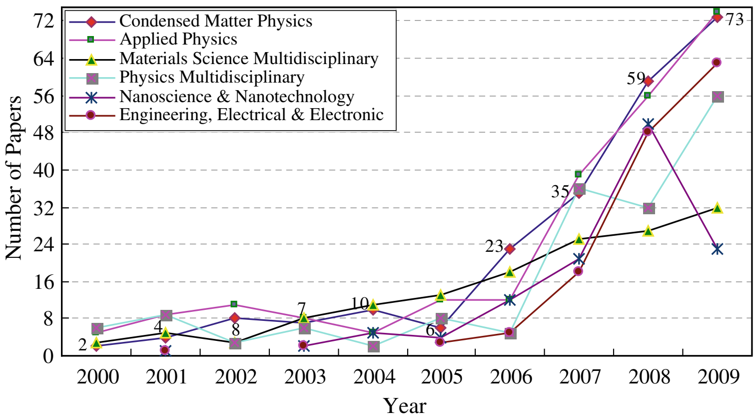

Fig. 13 Annual subjects distribution of CPCI papers

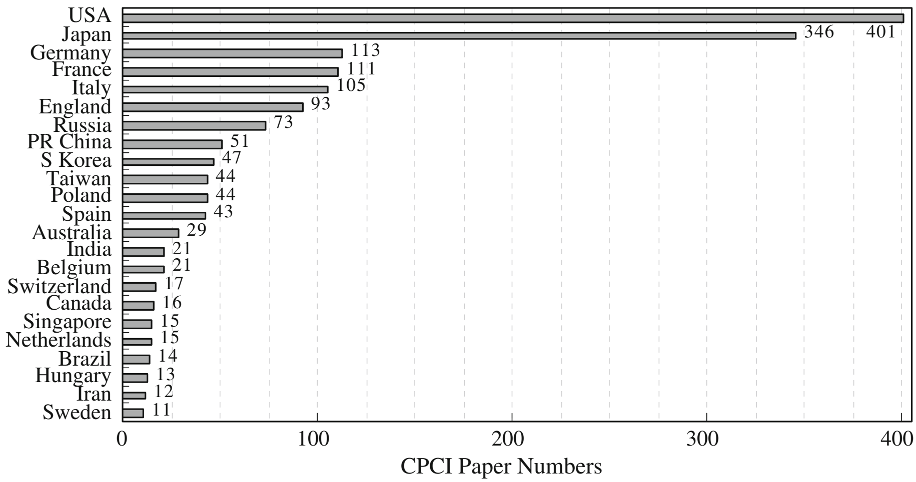

Fig. 14 Top productive countries of CPCI papers

Country of publication and International collaboration

The output from CPCI database is presented in Fig. 14, among which USA (25%) and Japan (21%) are the top countries in the graphene production. According to yearly detailed data, USA and Japan experienced ups and downs in the graphene research production and then they both got a great increase, during which USA published papers up-rushed in recent years. USA and Japan will still be the central producers of conference papers in near future.

Europe countries such as France, Germany, Italy, England and Russian were not as productive as they do. China ranked the seventh and articles from Taiwan were not included in China in proceeding papers. Europe countries and China kept a modest increase in the past decade.

Table 5 Top papers cited more than 100 times

Time cited	Authors	Title	Country	Institute	Conference	Year
301	Chen ZH, Lin YM, Rooks MJ	Graphene nano-ribbon electronics	USA	IBM Corp	2nd international symposium on nanometer-scale quantum physics, Tokyo, JAPAN	2007
131	Radovic LR, Silva IF, Ume JI	An experimental and theoretical study of the adsorption of aromatics possessing electron-withdrawing and electron-donating functional groups by chemically modified activated carbons	Portugal	Univ Nova Lisboa	Workshop on carbon materials for the environment, Charleston, SC	1997
109	Hill EW, Geim AK, Novoselov K	Graphene spin valve devices author and affiliation lines for the second affiliation	England	Manchester Ctr Mesosci & Nanotechnol	41st IEEE international magnetics conference, San Diego, CA	2006

Citation analysis of research publication

From Table 5 it can be seen that most high cited articles were produced by famous firms or corporations of developed countries. The most-frequently cited article “Graphene nano-ribbon electronics” was published by Chen Z.H of IBM Corporation. It showed that the advanced technologies in graphene were developed by big world class firms. The main topic of the high cited articles in proceedings laid on electronics as well as its device. This indicated that conferences were more concentrated on the application of graphene. Maybe more and more aspects of graphene applications will be reported first in the conference and included into proceedings after that.

Authorship and co-authorship of papers

An analysis of authors’ number, such as single author and co-author was undertaken in this article. Papers of single author were not as many as co-operated authors’ papers because modern research took many scientists to complete. The 2–8 authors’ term was the main body of the graphene research. Three or four authors’ articles increased dramatically after 2004, followed which were two or five authors’ term, and the less authors an article occupied, the more increasing it took.

Table 6 lists the eight kinds of articles taking different number of author affiliations. The single affiliation of papers’ author took the most big ratio, which means most papers were done by authors from a same organization. Authors come from more than two institutes worked together for a conference paper took a less ratio in the graphene research maybe indicate that conference papers stand for the level of one institute more than several ones.

Table 6 The author affiliation number of CPCI papers

Author affiliations number	1	2	3	4	0	5	6	7
CPCI Records	740	217	80	33	17	8	4	1
Rate (%)	67.27	19.72	7.27	3.00	1.55	0.73	0.36	0.10

Distribution of author keywords and co-words

Titles and author keywords provide reasonable details of the article subjects (He 1999). A total of 1,121 articles were analyzed. There were 1,560 keywords listed by authors, among which 1,230 keywords were used only once and 203 keywords were used twice. "Graphene" was the most frequently used author keyword (240; 54.92%), followed by "carbon nanotubes" (76; 17.39%) and "graphite" (48; 10.99%), as shown in Table 7. The word "carbon nanotubes" increased steadily from 2004 to 2009.

Data of keywords displayed the word of "graphene" increased sharply after it had been created. It can be expected that this new word will conduct the keywords of graphene research output in conference papers. The words "graphite" as well as "carbon" decreased in recent years when the new word "graphene" attracting many authors' attention.

Patents analysis

Patents, as a kind of output of technology-related activities, can be analyzed using bibliometric methods as scientific publications (Carel and Meyasedkfir 1993). Literature of graphene patents emerged mainly from 2000 and rose rapidly year by year in an index trend.

Patent production

The graphene related patents application in the past decade was shown in Fig. 15. It can be seen that the application formed a small peak in 2004 and raised fast after 2007. From 1 patent in 2000 to more than 300 in 2010, the graphene patents literature indicated that graphene has potential application value in near future and it will turn out to be more and more.

Subject categories of patents

According to Table 8, patents applications could be categorized mainly into six subjects in the research of graphene. From World Intellectual Property Organization (WIPO) international classifications, it can be concluded that the graphene patents application located in

Table 7 Keywords records of CPCI papers

Keywords	Graphene	Carbon nanotube(s)	Graphite	Nanostructured materials	Density functional theory/nanotubes	Electronic structure/ Raman spectroscopy
Records of CPCI	240	76	48	25	24	24
Rate (%)	54.92	17.39	10.99	5.72	5.49	5.49

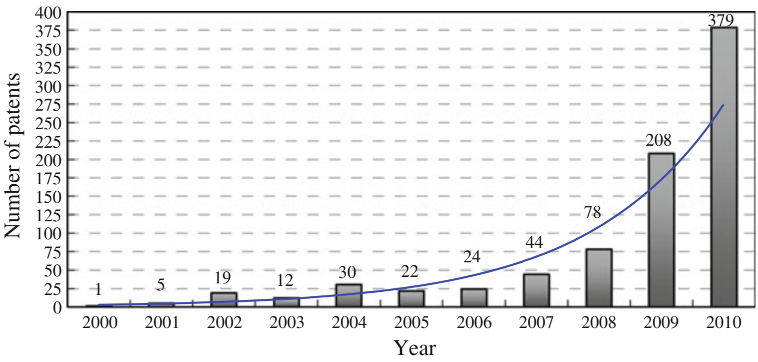

Fig. 15 Patents application from 2000 to 2010

Table 8 Subjects of main patents

International classifications	C01B031/00	C01B031/02	C01B031/04	H01L021/02	B82B003/00	H01L029/66
Subjects	Carbon; compounds; priority	Carbon; preparation; purification	Carbon; compounds; graphite	Manufacture or treatment of semiconductor devices	Nanostructures	Types of semiconductor device
Records	268	166	139	102	71	58
Rate (%)	33.33	20.65	17.29	12.69	8.83	7.20

the field of carbon and its compounds, semi-conduct devices and nanostructure. Most applications on graphene were in the range of carbon as shown in Fig. 16, especially the graphene application in the carbon related compounds increased rapidly maybe because that graphene derived from graphite.

Countries of patents

Top countries in graphene patents applications were shown in Fig. 17, which mostly distributed in US and Asia region such as Japan, South Korea and China. These countries covered 87% of patents in past ten years.

From the pie above, it can be concluded that 89.2% application was from US, Japan, South Korea, China and Germany. Figure 17 also explains the annual data of the top five countries in graphene application, showing that US and Japan applied their patents early around 2000 and increased rapidly after 2004, other countries started from 2005 and increased fast after 2007.

Distribution of author keywords

The topic of patents application can be obtained from the author keywords by cluster analysis. Clusters or co-words map of patents could image the core competency of the graphene research. Figure 18 was got from bibliometric analysis on the patents of graphene. It can be seen that these topics such as electrode cells device, graphite, exfoliated graphite process, nanotube related application, memory element, memory cell, edges

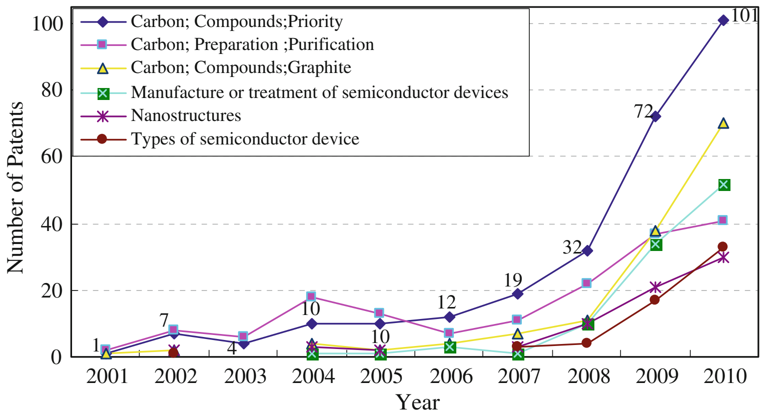

Fig. 16 Annual subjects distribution of patents

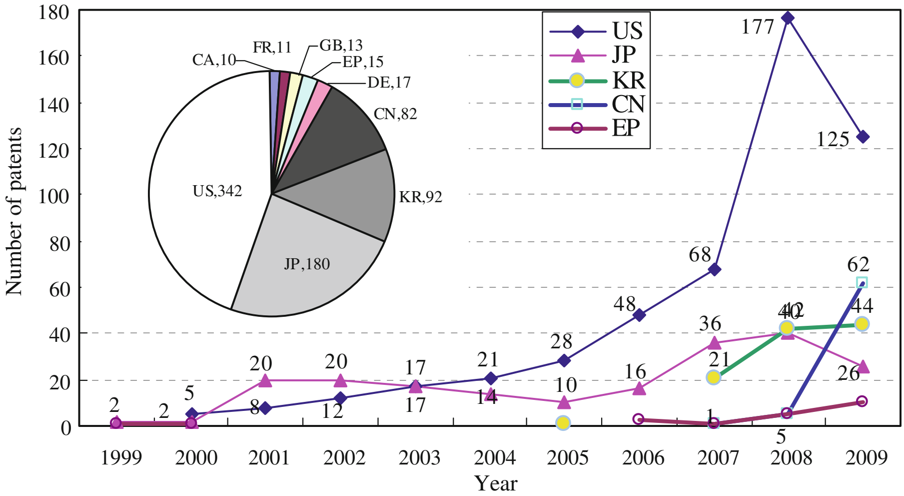

Fig. 17 Top productive counties and its annual application

hexagonal, hexagonal carbon stack, and gate device transistor were hot topics of the graphene research. These research fields will be the next potential technology application zone which worth more concentration.

Conclusions

In this study, the impact of global graphene literature has been studied by bibliometric methods and the research history has been recalled according to the graphene research literature (Barth and Marx 2008). Difficulties in progress of the graphene research were analyzed to summarize the rapid increase of research output, and some predominate work on graphene was also introduced. The graphene research presented an upward trend as the

Fig. 18 Patent topic visualization map

paper production increased steadily in the last decade, and the annual paper production in 2010 was about ten times that of the paper production in 2006. Based on the exponential model during 2005–2010, it can be predicted that, the number of scientific papers in 2012 on the topic of graphene will be at least twice of the number of publications in 2010.

The graphene research started in 1991 and boosted in the last decade. Graphene research mainly located in the subjects of physics and material science and developed very fast in recent years. As a new carbon material, graphene attracted lots of researchers' attention. All the output concentrated in several journals such as *Physics Review B*, *Physicas Review Letter* and *Applied Physics Letter*, and more than half (55% in 2010) graphene research papers were published about them in recent years. And *Physics Review B* was the chief journal for the graphene research, covering 60% research papers of graphene in 2010 already. As the warship, Journal of the *Physics Review B*, *Physicas Review Letter* and *Applied Physics Letter* published most of the articles. The research papers were mainly completed by two to five authors, and the team of three authors took larger and larger ratio. Two or four authors group turned less and less in the SCI and CPCI papers. Single writer for graphene papers decreased in 2010 showed that the collaboration in graphene research is reinforced.

The graphene research output distributed unevenly over all countries. USA, China and Japan were the top productive countries of SCI papers. To the CPCI paper or patents output, the top productive countries were USA, Japan, South Korea and China separately. Some Europe countries published less paper than these productive countries. The graphene research center is located in USA according to the data. The most frequently cited articles came from USA, England and Portugal, during which USA authors contributed most to the papers while England scientists contributed the most important part. The scientists from England obtained the Nobel Price for their graphene research. Several author keywords such as “graphene”, “carbon nanotubes” and “graphite” dramatically increased since 2006, which became the focus in the last few years, and might be a new research direction in the future. Through the keywords distribution trend it can be found that “graphene” and “carbon nanotubes” were the new emerging words and they will attract more and more researchers’ interesting. The key application of graphene patents was mainly concentrated in electrode device, transistor, etc. The application output will become more and more important since the properties of grapheme have been studied in detail.

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References

Barth, A., Marx, W. (2008). Graphene—a rising star in view of scientometrics. Physics and society (Physics.Soc-Ph) materials science (Cond-Mat.Mtrl-Sci). http://arxiv.org/abs/0808.3320.

Berger, C., Song, Z. M., et al. (2006). Electronic confinement and coherence in patterned epitaxial graphene. *Science, 312*(5777), 1191–1196.

Boyack, K. W., Klavans, R., et al. (2005). Mapping the backbone of science. *Scientometrics, 64*(3), 351–374.

Bullis, K. (2009). TR10: Graphene transistors. MIT Technology Review. http://My.Technologyreview.Com/Business/20242/.

Cappelli, E., Scilletta, C., et al. (2005). Surface characterisation of nano-structured carbon films deposited by Nd: YAG pulsed laser deposition. *Thin Solid Films, 482*(1–2), 305–310.

Carel, R. S., & Meyasedkfir, M. (1993). Repeated multiphasic screening examinations—evaluating the process. *Methods of Information in Medicine, 32*(3), 195–198.

Chen, W., Chen, S., et al. (2007). Surface transfer P-type doping of epitaxial graphene. *Journal of American Chemical Society, 129*(34), 10418–10422.

Chiu, W. T., & Ho, Y. S. (2007). Bibliometric analysis of tsunami research. *Scientometrics, 73*(1), 3–17.

Ciraci, S., Dag, S., et al. (2004). Functionalized carbon nanotubes and device applications. *Journal of Physics: Condensed Matter, 16*(29), R901–R960.

Cooper, C. (2003). Revisiting coauthor responsibility. *Science, 299*(5606), 511.

Enachescu, C., & Postelnicu, T. (2003). Patterns in journal citation data revealed by exploratory multivariate analysis. *Scientometrics, 56*(1), 43–59.

Faba-Perez, C., Guerrero-Bote, V. P., et al. (2003). Data mining in a closed web environment. *Scientometrics, 58*(3), 623–640.

Fernandez-Canon, J. M., Baetscher, M. W., et al. (2002). Maleylacetoacetate isomerase (MAAI/GSTZ)-deficient mice reveal a glutathione-dependent nonenzymatic bypass in tyrosine catabolism. *Molecular Cell Biology, 22*(13), 4943–4951.

Garfield, E. (1970). Citation Indexing for Studying Science. *Nature, 227*(5259), 669–671.

Geim, A. K., & Novoselov, K. S. (2007). The rise of graphene. *Nature Material, 6*(3), 183–191.

Hass, J., Varchon, F., et al. (2008). Why multilayer graphene on 4H-Sic(000(1)Over-Bar) behaves like a single sheet of graphene. *Physical Review Letters, 100*(12), 61–65.

He, Q. (1999). Knowledge discovery through co-word analysis. *Library Trends, 48*(1), 133–159.

Ilyin, A. M., Beall, G. W., et al. (2010). Simulation and study of bridge-like radiation defects in the carbon nano-structures. *Journal of Computational and Theoretical Nanoscience, 7*(10), 2004–2007.

Katsnelson, M. I., Novoselov, K. S., et al. (2006). Chiral tunnelling and the Klein paradox in graphene. *Nature Physics, 2*(9), 620–625.

Leydesdorff, L. (1997). Why words and co-words cannot map the development of the sciences. *Journal of the American Society for Information Science, 48*(5), 418–427.

Mccann, E., & Fal’ko, V. I. (2006). Landau-level degeneracy and quantum hall effect in a graphite bilayer. *Physical Review Letters, 96*(8), 086805-1–086805-4.

Nobelprize. (2010). The 2010 Nobel Prize in physics – press release. http://nobelprize.org/nobel_prizes/physics/laureates/2010/press.html.

Novoselov, K. S., Geim, A. K., et al. (2004). Electric field effect in atomically thin carbon films. *Science, 306*(5696), 666–669.

Novoselov, K. S., Geim, A. K., et al. (2005a). Two-dimensional gas of massless Dirac fermions in graphene. *Nature, 438*(7065), 197–200.

Novoselov, K. S., Jiang, D., et al. (2005b). Two-dimensional atomic crystals. *Proceedings of the National Academy of Science USA, 102*(30), 10451–10453.

Odegard, G. M., Gates, T. S., et al. (2002). Equivalent-continuum modeling of nano-structured materials. *Composites Science and Technology , 62*(14), 1869–1880.

Rajagopal, P. (2002). An innovation-diffusion view of implementation of enterprise resource planning (ERP) systems and development of a research model. *Information management, 40*(2), 87–114.

Science. (2009). Breakthrough of the year: The runners-up. *Science, 326*(5960), 1600–1607.

Sen, D., Novoselov, K. S., et al. (2010). Tearing graphene sheets from adhesive substrates produces tapered nanoribbons. *Small, 6*(10), 1108–1116.

Standley, B., Bao, W. Z., et al. (2008). Graphene-based atomic-scale switches. *Nano Letters, 8*(10), 3345–3349.

Su, H. N., & Lee, P. C. (2010). Mapping knowledge structure by keyword co-occurrence: a first look at journal papers in technology foresight. *Scientometrics, 85*(1), 65–79.

Tung, V. C., Chen, L. M., et al. (2009). Low-temperature solution processing of graphene-carbon nanotube hybrid materials for high-performance transparent conductors. *Nano Letters, 9*(5), 1949–1955.

Wallace, P. R. (1947). The band theory of graphite. *Physical Review, 71*(9), 622–634.

Wilk, G. D., Wallace, R. M., et al. (2001). High-kappa gate dielectrics: current status and materials properties considerations. *Journal of Applied Physics, 89*(10), 5243–5275.

Zhang, Y. B., Tan, Y. W., et al. (2005). Experimental observation of the quantum Hall Effect and Berry's phase in graphene. *Nature, 438*(7065), 201–204.