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Research Paper

Trends Analysis of Graphene Research and Development

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Citation: Lixue Zou, Li Wang, Yingqi Wu, Caroline Ma, Sunny Yu, & Xiwen Liu (2018). Trends Analytsis of Graphene Research and Development.

Vol. 3 No. 1, 2018
pp 82–100
DOI: 10.2478/jdis-2018-0005

Received: Jan. 15, 2018
Revised: Feb. 8, 2018
Accepted: Feb. 9, 2018

Abstract

Purpose: This study aims to reveal the landscape and trends of graphene research in the world by using data from Chemical Abstracts Service (CAS).

Design/methodology/approach: Index data from CAS have been retrieved on 78,756 papers and 23,057 patents on graphene from 1985 to March 2016, and scientometric methods were used to analyze the growth and distribution of R&D output, topic distribution and evolution, and distribution and evolution of substance properties and roles.

Findings: In recent years R&D in graphene keeps in rapid growth, while China, South Korea and United States are the largest producers in research but China is relatively weak in patent applications in other countries. Research topics in graphene are continuously expanding from mechanical, material, and electrical properties to a diverse range of application areas such as batteries, capacitors, semiconductors, and sensors devices. The roles of emerging substances are increasing in Preparation and Biological Study. More techniques have been included to improve the preparation processes and applications of graphene in various fields.

Research limitations: Only data from CAS is used and some R&D activities solely reported through other channels may be missed. Also more detailed analysis need to be done to reveal the impact of research on development or vice verse, development dynamics among the players, and impact of emerging terms or substance roles on research and technology development.

Practical implications: This will provide a valuable reference for scientists and developers, R&D managers, R&D policy makers, industrial and business investers to understand the landscape and trends of graphene research. Its methodologies can be applied to other fields or with data from other similar sources.

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Originality/value: The integrative use of indexing data on papers and patents of CAS and the systematic exploration of the distribution trends in output, topics, substance roles are distinctive and insightful.

Keywords Graphene; R&D distribution; Topic distribution and evolution,; Substance roles distribution and evolution; Text mining

1 Introduction

Today, R&D plays important roles in enhancing national competitiveness and sustainability. Many traditionally scientifically under-developed countries are now catching up and the global R&D landscape has seen dramatic changes. Facing the continuing competition, researchers, technology innovators, and policy makers all need to grasp the structure and developments of global research and innovation, so dynamical monitoring and dignosing of research fields become a strategic endeavor at higher levels of research planning and policy making.

Materials science is the foundation for many emerging industries. Graphene (Novoselovl et al., 2004), due to its outstanding electrical, thermal, and optical properties, has great potential for applications in energy, environment, electronics, biology and other fields. As a result, graphene research is gaining intensive attention world-wide. Many countries have embarked on R&D prgrams on graphene to position themselves among the leaders.

Scientometric analysis has recently been applied to map global trends of graphene research using publications or patent data. Evidence from such analysis shows that graphene research increased over past 20 years and saw an up-ward burst in recent 5 years (Lv et al., 2011). However, exponential growth in published articles has met with a decreasing average citation per article and diminishing share of highly-cited publications (Klincewicz, 2016; Zheng, 2016). Some attributed recent rising number of publications on graphene to the fact that researchers working in carbon nanotubes gradually move towards study of graphene (Etxebarria, Gomez-Uranga, & Barrutia, 2012). The growth complexity may also be due to graphene's growing applications in non-electronics areas, such as health, environment, and energy (Klincewicz, 2016).

Some bibliometric analysis studies on global graphene research also included patent data. Researchers investigated graphane-related patents, with parameters like the time of application, the technology fields the patents belong to, applicants (Zhao & Chen, 2016), subjects, patentee's technical strength, and Highly Cited Patents, to reveal the innovation trends (Zheng, 2016; Le & Polytechnic, 2017). A few papers compared the publications and patents on graphene to reveal the relationship between research and innovation (Peng, 2016). Still, a detailed and large scale analysis of graphene R&D is needed to fully reveal the landscape (Li, 2015).

The current paper uses publication data for research and patent data for innovation to study the trends of graphene R&D. Both types of data are provided by Chemical Abstracts Service (Perianes-Rodriguez, Waltman, & Eck, 2016; Retrieved from http://www.cas.org/) (CAS) of the American Chemical Society. Using structured index data from CAS databases, this study focuses on the growth and distribution of R&D outputs, topic distribution and evolution, distribution and evolution of substance properties and applications, and other aspects of the global graphene R&D.

2 Data and Methods

2.1 Data Collection

CAplus database was searched for documents including "graphene" (case insensitive) in their subject or concept metadata, along with documents using the CAS Registry number for substance of graphene in CAS Registry. A set of 78,756 articles wereretrieved by April 5, 2016 for those published from 1985 to March 2016. Types of publications include journal articles, preprints, conference articles, dissertations, and books. 23,057 patents were obtained by April 5, 2016 for those applied from 1997 to March 2016. XML data files from CAS weremapped into an internal processing file format. Then, CAS indexing terms for topic, concept, substance, commercial or government entity, source of publication, and various other data entities, were extracted for analysis.

2.2 Data Analysis Process

The investigations were conducted as follows:

(1) Country/region distribution of publications and patents

A global map was drawn to illustrate the numbers of patents and publications of each country/region, using the country/region of the first author affiliation as the basis. Top five producer countries were identified for both publications and patents. Then, for top 5 countries, the ratio of patents applied in other four countries to the total patents in each country was calculated, to demonstrate the patent flow in major countries.

(2) Description of the leading organizations in R&D

Based on the number of papers or patents, we selected the top 20 research institutions with each assigned accordingly as university, research institute, or enterprise. In addition, we measured the year ranges that each organization has been active in research in graphene, and the percentage of output in the last three years to indicate the activeness of the institution. Moreover, using the concept indicators in publication metadata, we extracted the high-frequency concepts as top terms and high frequency concepts in last three years as recent terms, to demonstrate the hot research areas of the top 20 organizations. The IPC categories of patent applications are listed to show the technology area distribution in detail.

(3) Substaces and application roles distributions

Substances are indexed for papers and patents by CAS, and the roles of substances are identified and divided into super roles and specific roles. This enables exploration of the substances role distribution in graphene research. For the specific roles, the distribution by year of the top 20 roles were analyzed; for the super roles, role evolutions from 2010 to 2016 were studied via three time slices, respectively 2010–2011, 2012–2013, and 2014–2016 where data for 2016 was incomplete. Because the role change was not obvious before 2009, data for 2008–2009 was added only for reference.

(4) Subject clustering of publications and patents

Clustering of the publications and patents were conducted using the indexed concepts by CAS using the sofeware VOSviewer (Eck & Waltman, 2010, 2011). A visualized bibliometric network based on co-occurence (Eck & Waltman, 2009) was produced. Then, experts were invited to interpret the topics for each cluster. Furthermore, timelines were introduced to reveal the topics evolution. In addition, emerging terms, defined as those appering first time compared to all the early times, were detected for each of the periods of pre-2010, 2010–2011, 2012–2013, 2014–2016.

3 Results

3.1 Overall growth of graphene R&D

Figure 1 gives the overall growth of grapheme R&D. Publications or patents before 2000 were very limited, 336 and 2 respectively, so only data since 2000 were shown. The growth seemed very slow until the groundbreaking isolation of graphene for the first time in 2004 sparked a global explosion in graphene research. Both papers and patents started rapid increase since 2005, especially after 2010. Over 50 percent of papers and patents output were during 2014–2016, and the increase looks still strong, though some leveling-off may be ahead.

3.2 Country/region distribution

3.2.1 Overall country/region distribution

The country/region distribution of publications was produced as Figure 2. Those with total numbers of over 2000 are shown in red. Five top producers are China (excluding Hong Kong, Macao and Taiwan, similarly hereinafter), United States,

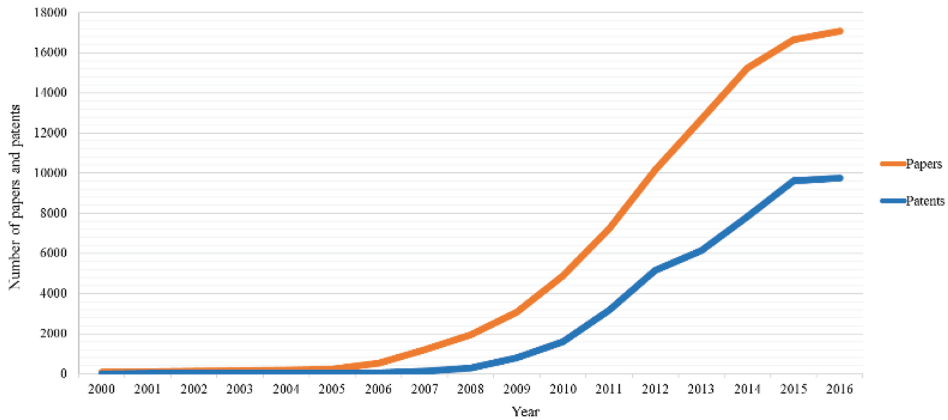

Figure 1. Papers and patents in graphene research by year.

South Korea, Japan and India. They together accounted for 64.3 percent of the global total. The distribution of patent applicant countries was also analyzed where the top five countries are China, South Korea, United States, Japan and Germany. They together accounted for over 90 percent of the global patents in graphene.

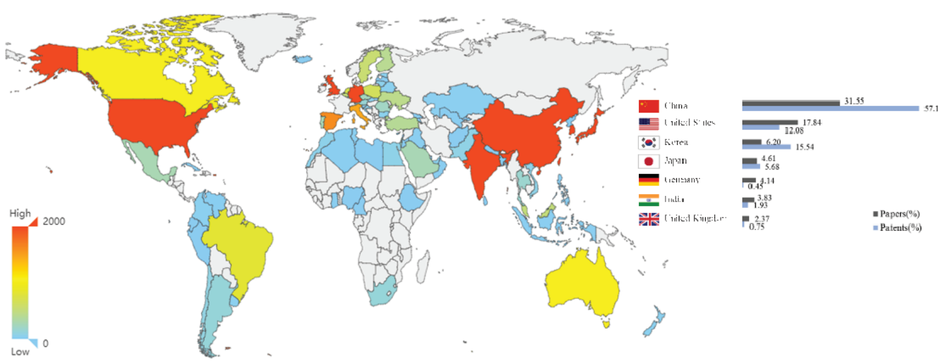

Figure 2. Country/region distribution in graphene R&D.

3.2.2 R&D distribution of top five countries by year

Figure 3 gives the relative outputs of the top five countries from 2000 to 2015. From the retrieved data, we know that the United States and Japan published their first papers in graphene in 1985 and 1992, respectively, and went strong until around 2010 when their publications began level-off and even began to decline after 2013. In contrast, publications from China has grown dramatically after 2010, surpassing the United States. The publications from South Korea overtook Japan since 2010, but increased only slowly afterwards, to be in similar strength as India in recent years. Nearly half of the publications from China and South Korea were produced during 2013–2015.

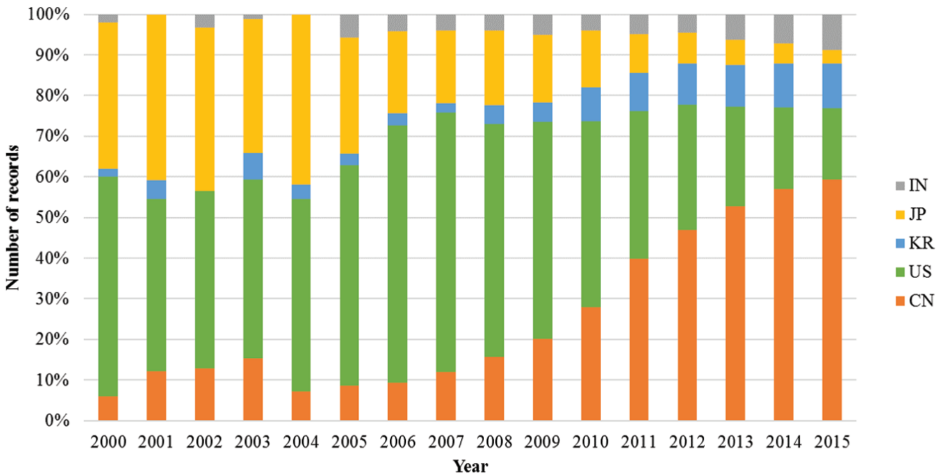

Figure 3. Papers by the top five countries.

As for patent applications, data since 2001 were shown in Figure 4 for the top five countries identified in Figure 2. The United States and Japan applied their first patents in 1997 and 1999, respectively, but their applications began to drop considerably around 2008–2010. In contrast, the number of patents applied from China started since 2007 and increased dramatically ever since, with 2012 saw that China applied more than 50% of the world total, while the other four countries faced steady declination.

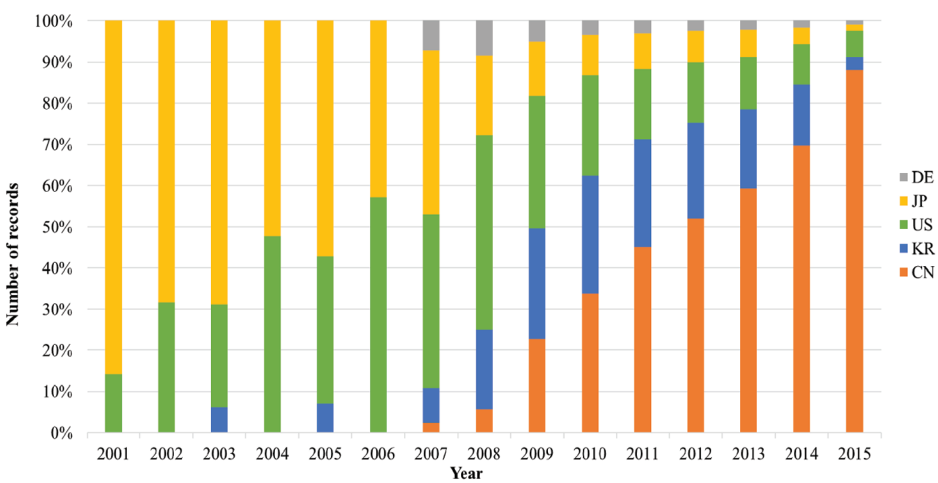

Figure 4. Patents by the top five countries.

3.2.3 Patent application flows in the top five countries

Figure 5 illustrates the flows of patent applications among the top five countries. The width of the arrows is proportional to the patent applications originated from one country to be applied in other countries. The majority of patent applications flew to United States and China. Although the total number of patent applications of China is high, only 2.3 percent of them are done in other countries. In contrast, the ratios that Korea, United States, Japan and Germany applied patents in other four countries are 27.8%, 24.8%, 32.3% and 45.3%, respectively. While Chinese institutes applied the largest number of patents, most were applied only in China.

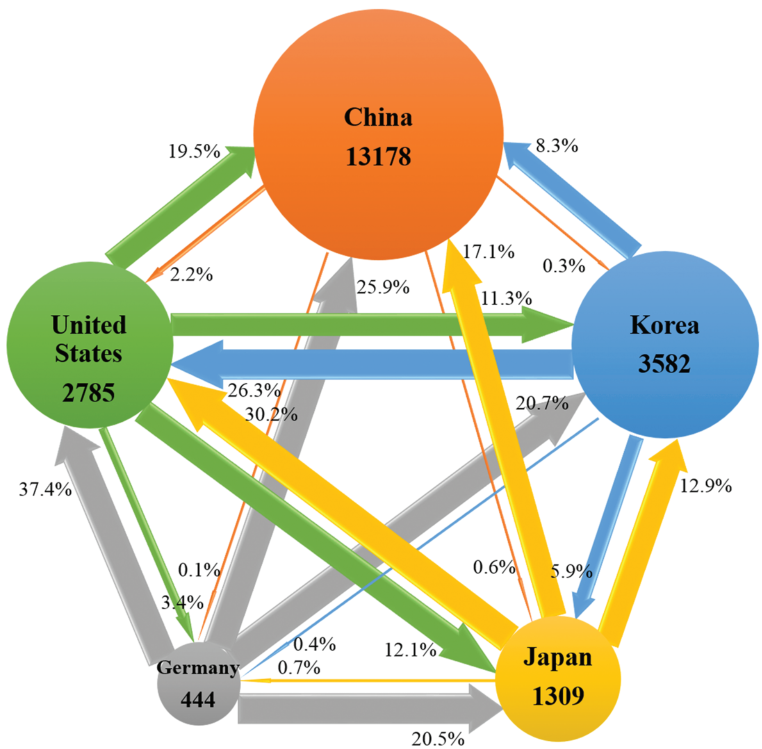

Figure 5. Patent application flow in main countries.

3.3 Top R&D producers

3.3.1 Top research organizations

Table 1 lists the top 20 organizations in terms of publications, 11 are in China, three in the United States, two in South Korea, two in Singapore, one each from Japan and Russia. 18 out of the 20 are universities, while the remaining two are

Table 1. Top 20 organizations in graphene research papers.

Organization	Country	Papers	Type	Years R	Percentage (Last3 Years)	Top Terms	Recent Terms
Chinese Academy of Sciences	CN	2,973	Institute	1997–2016	45%	Raman spectra; Nanocomposites; Surface structure	Electrolytic polarization; Photothermal therapy; Mammary gland neoplasm
University of California	US	1,296	University	1994–2016	26%	Band structure; Electric conductivity; Raman spectra	Optical instruments; Thin film transistors; Ferroelectricity
Nanyang Technological University	SG	890	University	2001–2016	38%	Raman spectra; Nanoparticles; Surface structure	Transition metal ; Encapsulation; Photoluminescence
Tsinghua University	CN	739	University	1998–2016	44%	Raman spectra; Electric conductivity; Chemical vapor deposition	Pore structure; Ion transport; Dielectric films
Russian Academy of Sciences	RU	738	Institute	1999–2016	38%	Electric conductivity; Density of states; Band structure	Lennard-Jones potential; Surface acoustic wave; Magnetocaloric effect
National University of Singapore	SG	712	University	2000–2016	30%	Nanoribbons; Electric conductivity; Raman spectra;	Flexibility; Permeability; Battery electrolytes
The University of Texas	US	672	University	2004–2016	25%	Band structure; Electric conductivity; Field effect transistors	Band offset; Melting point; Raman spectroscopy
University of Science and Technology of China	CN	616	University	2003–2016	41%	Nanocomposites; Nanosheets; Electric conductivity	Phase composition; Atomic layer deposition; Photocatalysts
Peking University	CN	563	University	1996–2016	44%	Raman spectra; Chemical vapor deposition; Band structure	Superconductivity; Semimetals; Cathodes
Fudan University	CN	516	University	1994–2016	43%	Nanocomposites; Nanosheets; Nanoparticles	Shubnikov-de Haas effect; Chronoamperometry; Crystal orientation

Organization	Country	Papers	Type	Years R	Percentage (Last3 Years)	Top Terms	Recent Terms
Zhejiang University	CN	509	University	1997–2016	55%	Nanosheets; Raman spectra; Nanocomposites	Open circuit potential; Adsorptive wastewater treatment; Heterojunction solar cells
Nanjing University	CN	468	University	2002–2016	46%	Nanoparticles; Nanocomposites; Surface structure	Crystal morphology; Drug delivery systems; Electrochemical analysis
Massachusetts Institute of Technology	US	458	University	1989–2016	30%	Raman spectra; Chemical vapor deposition; Electric conductivity	Thermoelectricity; Laser heating; Optical conductivity
Sungkyunkwan University	KR	446	University	2007–2016	50%	Raman spectra; Chemical vapor deposition; Field effect transistors	Double-layer capacitor electrodes; Aerogels; Aminoplasts
Jilin University	CN	414	University	2008–2016	49%	Nanocomposites; Nanoparticles; Surface structure	Lithium-ion secondary batteries; Thermal analysis; Contact angle
Shanghai Jiao Tong University	CN	397	University	2005–2016	52%	Nanocomposites; Electric conductivity; Nanosheets	Lithium-ion secondary batteries; Aerogels; Electrochemical reaction catalysts
Seoul National University	KR	392	University	2004–2016	49%	Raman spectra; Surface structure; Electric conductivity	Capacitors; Intercalation; Conducting polymers
Tohoku University	JP	370	University	1998–2016	26%	Band structure; Electric conductivity; Fermi level	Far-IR detectors; Grain size; Hot electrons
Hunan University	CN	368	University	2001–2016	61%	Nanoparticles; Nanocomposites; Cyclic voltammetry	Lithium-ion secondary batteries; Mid-IR spectra; Chemical potential
Tianjin University	CN	359	University	2003–2016	57%	Nanoparticles; Raman spectra; Nanosheets	Lithium-ion secondary batteries; Solar cells; Thickness

research institutes, indicating that graphene research is dominated by universities and research institutes.

Major research topics for each of the top 20 were obtained using methods described in Section 2. It shows that Chinese organizations mainly focus on sensors, electronics and photovoltaics, and batteries, while US ones concentrated more on photoelectric properties, electronic structure, thin film transistors and semiconductors. Organizations from South Korea deal more on capacitors while the Japanes one focuses on electric properties.

3.3.2 Top patent applicants

20 top global graphene patent applicants are listed in Table 2. Among them, 14 were from China, four from South Korea and two from the United States. In addition, 15 assignees were universities or research institutes while the other five were enterprises.The top five were Chinese Academy of Sciences, Samsung Electronics, Ocean's King Lighting Science & Technology, Zhejiang University, and LG Electronics. The major technology topics of patent applications for the top 20 organizations indicated that Chinese assignees applied patents more in preparation, batteries and composites, while the assignees from South Korea focused mainly in semiconductors devices and batteries and those from the United States primarily in semiconductors devices.

3.4 Research category distribution

The Discipline/Specialty Sections assigned by CAS to each indexed paper and patent were used to give an overview of the research areas of graphene. As shown in Figures 6, graphene R&D have scattered in many Sections such as Electric Phenomena, Electrochemical, Radiational, and Thermal Energy Technology, Optical, Electron, and Mass Spectroscopy and Other Related Properties, Surface Chemistry and Colloids, Ceramics, General Physical Chemistry, Biochemical Methods, Plastics Manufacture and Processing, Electrochemistry and Magnetic Phenomena. Of these, there is a gradual increase in R&D effort in Electrochemical, Radiational, and Thermal Energy Technology, Optical, Electron, and Mass Spectroscopy and Other Related Properties, Biochemical Methods, Plastics Manufacture and Processing, and Electrochemistry, as indicated by the percentage change of coverage in these areas over the years.

Analysis of technological areas was made using IPC (International Patent Classifications) data of the patents data, as shown in Figure 7. The highest concentrations are in graphene preparation, composites and batteries.

In 2013–2015, innovation in the following IPC categories are active: C08K0013/06 (Pretreated ingredients), C09D0007/12 (Other additives), H01M0010/0525 (Lithium

Table 2. Top 20 applicants in graphene research papers.

Organization Names	Countries	Patents	Type	Year Range	Percentage (Last 3 Years)	Top Terms	Recent Terms
Chinese Academy of Sciences	CN	1,299	Institute	2007–2015	37%	Fluoropolymers Chemical vapor deposition Films	Three-dimensional printing Heat stabilizers Crystals
Samsung Electronics Co., Ltd.	KR	515	Enterprise	2007–2015	16%	Electrodes Electroluminescent devices Semiconductor device fabrication	Chalcogenides Binding energy Lithium primary batteries
Ocean's King Lighting Science & Technology Co., Ltd.	CN	439	Enterprise	2010–2013	0%	Composites Secondary batteries Fluoropolymers	-
Zhejiang University	CN	270	University	2008–2015	49%	Fluoropolymers Secondary batteries Nanocomposites	Photoelectric cell electrodes Electric cables and wires Flexibility
LG Electronics, Inc.	KR	258	Enterprise	2009–2015	33%	Secondary batteries Electroluminescent devices Fluoropolymers	Aromatic hydrocarbons Polycyclic aromatic hydrocarbons Petroleum pitch
Harbin Institute of Technology	CN	222	University	2010–2015	61%	Composites Fluoropolymers Secondary batteries	Lithium-ion secondary batteries Aerogels Direct methanol fuel cells
Tsinghua University	CN	213	University	2009–2015	36%	Secondary batteries Electrodes Fluoropolymers	Cathodes Electron emission Fuel cell cathodes
Shanghai Jiao Tong University	CN	187	University	2009–2015	41%	Composites Secondary batteries Fluoropolymers	Electrolytic capacitors Electrolytes Paper
International Business Machines Corporation	US	186	Enterprise	2005–2015	11%	Dielectric films Field effect transistors Semiconductor device fabrication	Electrolytes Surface plasmon resonance Tunneling
Korea Advanced Institute of Science and Technology	KR	185	Institute	2008–2015	16%	Nanowires Nanostructures Nanoparticles	Distributed Bragg reflectors Energy storage systems Varistors
Southeast University	CN	154	University	2010–2015	44%	Composites Heat treatment Nanoparticles	Impregnation Injection molding Orthopedic prosthetics
Jiangsu University	CN	140	University	2010–2015	54%	Nanocomposites Photolysis catalysts Nanoparticles	Aerogels Double layer capacitors Electric capacitance

Organization Names	Countries	Patents	Type	Year Range	Percentage (Last 3 Years)	Top Terms	Recent Terms
University of Jinan	CN	137	University	2010–2015	63%	Antibodies and Immunoglobulins Immunosensors Blood serum albumins	Magnetic separation Amination Prostate-specific antigen
Beijing University of Chemical Technology	CN	135	University	2009–2015	41%	Styrene-butadiene rubber Natural rubber Nanoparticles	Fireproofing agents ABS rubber Acrylic rubber
Fudan University	CN	133	University	2010–2015	48%	Electrodes Composites Lithium-ion secondary batteries	Lithium-ion secondary batteries Double layer capacitors Electrospinning
University of Electronic Science and Technology of China	CN	130	University	2010–2015	36%	Coating process Films Polyesters	Electric resistance Interference Optical modulators
Shanghai University	CN	129	University	2009–2015	62%	Composites Fluoropolymers Secondary batteries	Lithium-ion secondary batteries Aerogels Dispersion of materials
Donghua University	CN	120	University	2010–2015	48%	Fluoropolymers Composites Polyoxyalkylenes	Coupling agents Glass microspheres Pharmaceutical carriers
Korea Institute of Science and Technology	KR	117	Institute	2008–2015	21%	Polyimides Solar cells Nanoparticles	Enterobacteria phage M 13 Hydrogels Peptides
Baker Hughes Inc.	US	107	Enterprise	2008–2015	12%	Nanoparticles Fullerenes Silsesquioxanes	Crosslinking agents Ferrofluids Magnetic materials

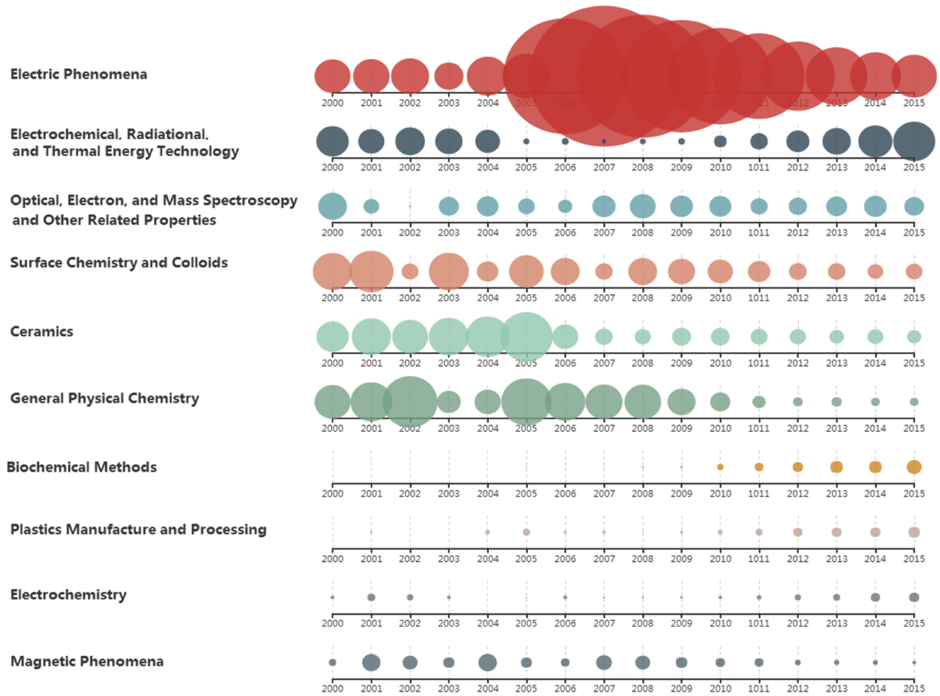

Figure 6. Distribution of global research categories as assigned by CAS.

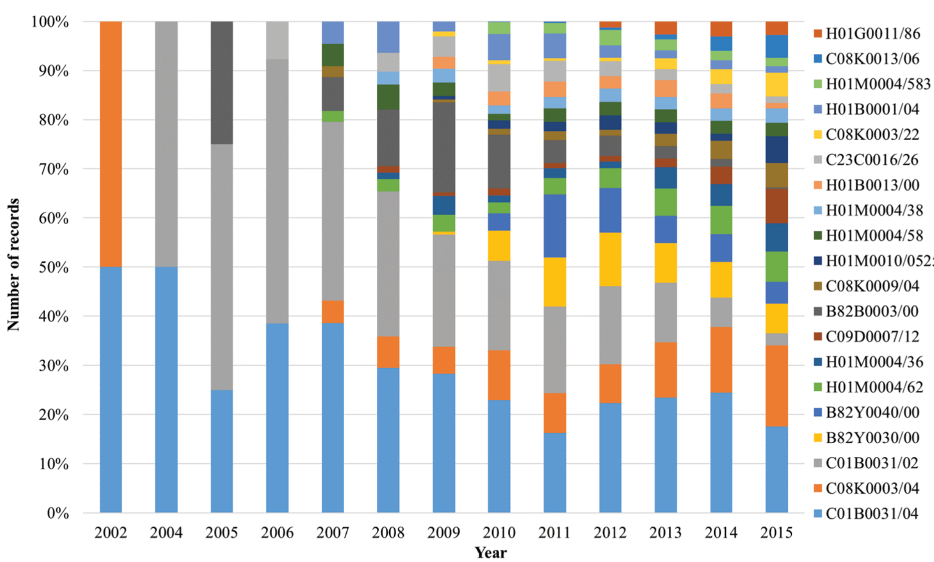

Figure 7. Main technology areas distribution by year.

batteries), and H01G0011/86 (Capacitors, specially adapted for electrodes), while the number of applications in the following IPC categories are relatively low: H01B0001/04 (Mainly consisting of carbon-silicon compounds, carbon, or silicon), and H01B0013/00 (Apparatus or processes specially adapted for manufacturing conductors or cables). The patents in the nanocomposites related IPC B82Y0030/00 (Nanotechnology for materials or surface science) and B82Y0040/00 (Manufacture or treatment of nanostructures) declined since 2012.

3.5 Research topic evolution

3.5.1 Research topics evolution

The evolution of graphene research topics was analyzed using the concepts of papers and patents indexed by CAS. Considering the dramatic increase after 2010, the data set was divided into two time windows, 1985–2009 and 2010–2016 (Figure 8 and 9, respectively). Two networks show that before 2009, graphene research mainly focused on the mechanical and other properties and electrical properties. But since 2010, it has extended continuously into a diverse range of potential applications, such as batteries, capacitors, semiconductors, and sensorsdevices.

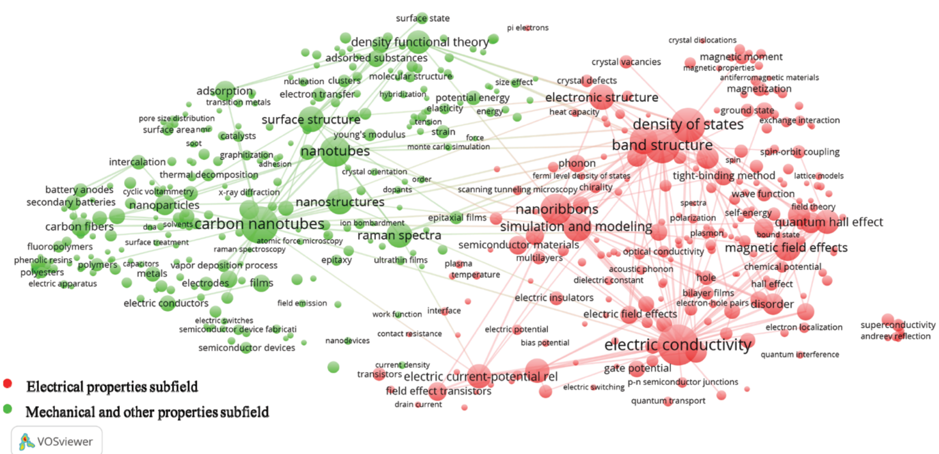

Figure 8. Topics distribution of papers and patents in graphene research (before 2009).

3.5.2 Emerging terms in graphene R&D

Indexed concepts in papers and patents were analyzed to detect emerging concepts and their percentages among all the indexed terms, in four periods: before 2009, 2010–2011, 2012–2013, and 2014 and after, as in Figure 10. The sizes of the pie charts are proportional to the numbers of concepts and the orange color parts

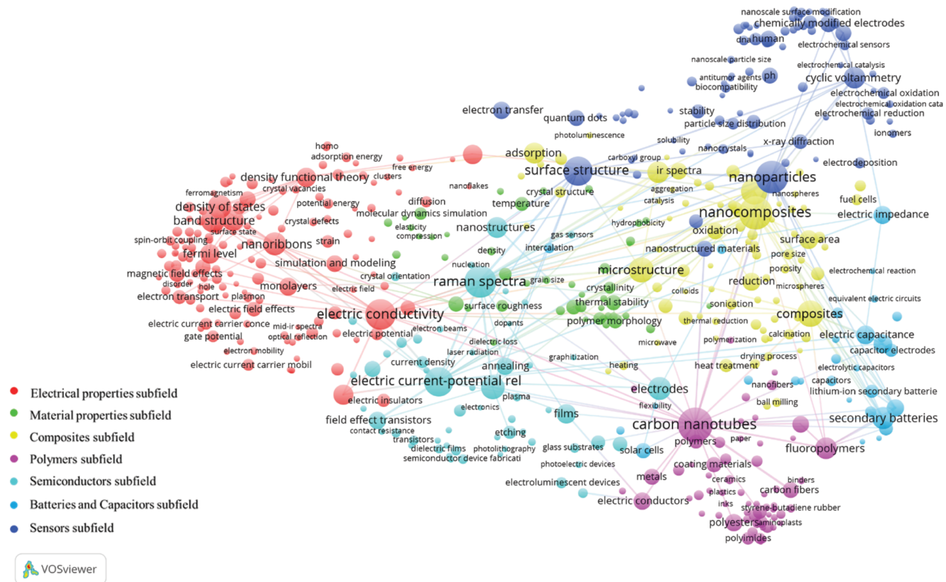

Figure 9. Topics distribution of papers and patents in graphene research (2010–2016).

represent the percentages of emerging terms. Emerging concepts increased remarkably after 2010 and the trend correlated with widening of research and innovation into diverse fields, indicating the vitality of graphene R&D and potential for new break-throughs.

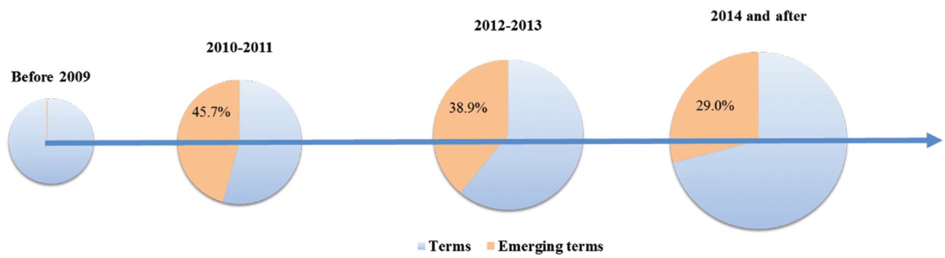

Figure 10. Evolution of emerging terms of global papers and patents.

3.6 Substance roles distribution & evolution

3.6.1 Substance role distribution

Substance roles indexed by CAS in the papers and patents were examined (Figure 11). 39.9 percent are USES, including TEM (Technical or Engineered Material Use), MOA (Modifier or Additive Use), CAT (Catalyst Use), NUU (Other Use, Unclassified); 20.8 percent are Special, including PRP (Properties) and NAN

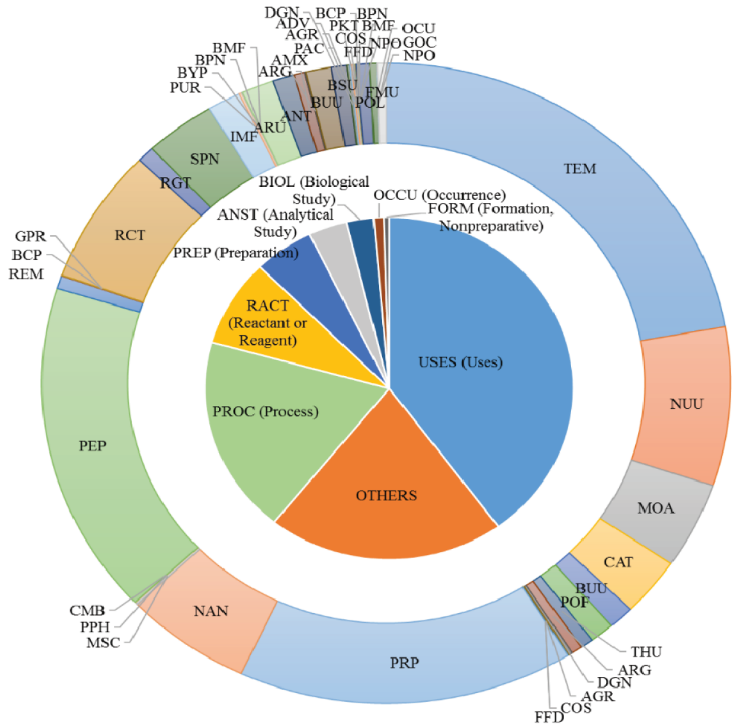

Figure 11. Role distribution of substances reported in graphene research.

(Nanoscale Substances/Materials); 18.6 percent are PROC (Process), including PEP (Physical, Engineering or Chemical Process) and REM (Removal or Disposal).

3.6.2 Subtances role distribution evolution

Time distribution for substances roles was given in Figure 12. PRP (Properties) has declined since 2006; NAN (Nanoscale Substances/Materials), IMF (Industrial Manufacture), RGT (Reagent), CAT (Catalyst Use) have decreased since 2009; PEP (Physical, Engineering or Chemical Process) has remained constant since 2011; TEM (Technical or Engineered Material Use), ANT (Analyte), BSU (Biological Study, Unclassified), POF (Polymer in Formulation) have decreased since 2012. In contrast, BUU (Biological Use, Unclassified) has increased since 2008, MOA (Modifier or Additive Use), POL (Pollutant) and REM (Removal or Disposal) grew year on year. In general, the main roles declined recently while roles in Biological Use, Modifier or Additive Use, Pollutant, Removal or Disposal have become new focuses.

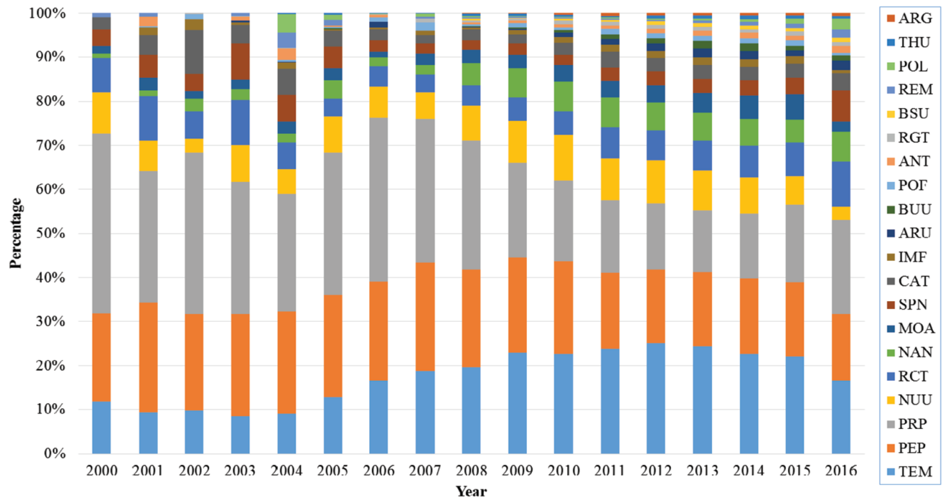

Figure 12. Role trends of substances reported in graphene research.

3.6.3 Evolution of emerging substance roles

Time slice analysis was used to examine the evolution of emerging substance roles in graphene research (Figure 13). Based on the emerging substances, roles in USES and PROC (Process) have declined in recent years. On the contrary, the roles in PREP (Preparation) and BIOL (Biological Study) increased over time.

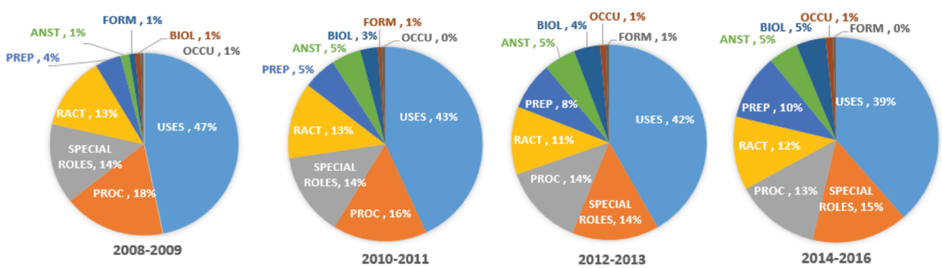

Figure 13. Role evolution of emerging substances in graphene research.

4 Discussion

In summary:

(1) In recent years, the numbers of both papers and patents in graphene continued their increases, indicating that R&D in graphene is still growing.

(2) China, United States, South Korea and Japan hold considerable technological advantages. United States and Japan developed their research and innovation earlier than China and South Korea, but China has become the largest R&D producer in recent years.

(3) Major Chinese graphene R&D actors are mainly universities and research institutes, while the R&D efforts in South Korea and the United States are dominated by enterprises. Chinese applications for patents concentrated mainly on preparation, batteries and composites, whereas South Korean organizations applied for patents mainly in semiconductor devices and batteries and US organizations did so primarily in semiconductor devices.
(4) The industrialized application of graphene materials is continuously expanding from mechanical, material, and electrical properties to a diverse range of potential applications such as batteries, capacitors, semiconductors, sensors, and semiconductors devices. The constant occurrences of the emerging terms in recent years also indicate a robust and diversifying R&D field.
(5) The roles of emerging substance roles tend to increase in Preparation and Biological Study over time, suggesting that the innovative application of graphene has caught the attention. And, it seems that the technology for preparing graphene materials will still be a major focus for the near future. Wide application of graphene in fields such as energy, biology, electronics and nano-composite materials, requires low-cost, green preparation processes, high-quality fine structure control and multilevel multifunctional assembly and integration. Development, improvement and optimization of preparation methods and techniques will be needed to maximize all the outstanding qualities of graphene.

In conclusion, graphene research and development has shown promising application potential across a wide range of fields, but challenges still exist in technological breakthrough in its preparation methods and processes in order to realize its industrialization for leading innovation in next-generation materials.

Acknowledgement

Special acknowledgement is to Mr. Matthew Toussant who gave us considerable guidance on project planning and implementation, Mrs. Cynthia Liu and Mr. Todd Chamberlain who supported us with data provision, and the experts in the field of graphene provided the detailed scientific interpretation.

Author contributions

Lixue Zou (zoulx@mail.las.ac.cn, corresponding author) conceived and designed the analysis, contributed data or analysis tools, performed the analysis and wrote the paper. Li Wang (wangli@mail.las.ac.cn) conceived and designed the analysis, contributed data or analysis tools. Yingqi Wu (ywu@cas.org), Caroline Ma (cma@acs-i.org) and Sunny Yu (syu@acs-i.org) collected the data. Xiwen Liu (liuxw@mail.las.ac.cn) conceived and designed the analysis.

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