Global Science & Technology Trends Report: Graphene Research & Development

National Science Library, Chinese Academy of Sciences
Chemical Abstracts Service, American Chemical Society

May, 2017
Foreword

A global technological and industrial revolution is beginning, while breakthroughs on fundamental scientific questions, such as the origin of the universe, matter, life, and cognition are beginning to take shape. The pace of development in fields such as materials, energy, healthcare and information is accelerating. New technological breakthroughs continuously emerge, causing disruption in traditional industries. The pace of innovation is accelerating with unprecedented speed, depth and breadth, changing the global innovation landscape and driving increased industrial competition, as well as impacting social and economic structures and people’s everyday lives.

Since its discovery and isolation in 2004 by British scientists Andre Geim and Konstantin Novoselov, graphene has attracted worldwide attention due to its unique properties and potential impact on interdisciplinary materials research. Researchers and practitioners in the graphene field have high hopes for breakthroughs in research and development as well as disruptive applications.

Universities, public research institutes and commercial enterprises around the world, especially in countries like the U.S., China, the UK, Germany and South Korea, are actively engaged in R&D and commercialization of graphene materials. Competition is fierce to secure an intellectual property footprint in graphene technologies and applications as well as to occupy the high end of the value chain in this emerging industry. The Chinese government rapidly initiated a series of research and development programs focused on graphene at the national level, and many local governments in China have also planned to establish graphene industrial parks and tech research institutes to support local development of graphene technology and new products. In this way, a complete graphene industry chain is being formed, from raw materials, preparation and product development, to downstream product applications. However, there is still opportunity to strengthen and deepen fundamental graphene research efforts. Further development of techniques and methods to optimize performance and large-scale production is needed.
The National Science Library (NSL), Chinese Academy of Sciences and CAS (Chemical Abstracts Service), a division of the American Chemical Society, collaborated to complete a big data analytics and visualization project that reveals global trends in the emerging field of graphene technology. Areas addressed include level of innovation, regional R&D landscape and scientific research competitiveness. The resulting analysis provides a valuable reference for organizations focused on science and technology innovation in this space and may inform the planning of research projects and commercialization efforts.

NSL and CAS plan to build a long-term, in-depth cooperation that will provide deeper and broader perspectives on high-impact scientific and technical fields through advanced information analysis. We will focus on cutting-edge technologies and those with the greatest potential to cause disruption. Through this collaboration, we look forward to sharing a series of professional, authoritative and widely influential reports on global science and technology trends that will provide more comprehensive and precise information support and knowledge services for scientists, research administrators, entrepreneurs and government departments supporting technology and industry.

Dr. Chunli Bai
President
Chinese Academy of Sciences
Preface

In today’s knowledge economy, countries around the globe understand the importance of developing strength in strategic areas of science and technology to enhance national competitiveness and cultivate new industries that will drive economic growth. Around the world, new geographic patterns of knowledge and innovation are emerging as the global distribution of innovation and R&D models in science and technology are changing. Government policy makers, investors, and scientific researchers are concerned with understanding the global research landscape of emerging technologies and keeping up to date with the worldwide development trends of science and technology. Actively monitoring and tracking dynamic development trends in key fields and undertaking objective research and analysis are critical priorities for those who manage research and development.

The new materials industry is the foundation of a number of strategic emerging fields. Graphene is a shining pearl in the modern materials industry due to its outstanding electrical, thermal, optical and other properties. It has great potential for applications in energy, environment, electronics, biology and other fields. As a result, graphene is gaining worldwide attention and is seen as an important material that will play a key role in future high-technology competition and is thus of strategic importance. Many countries have initiated a large number of diverse graphene R&D projects in order to gain a leadership position in key technology fields and strive to develop global competitive advantages in technology, industry and economy.

In order to enhance understanding of the landscape and development trends in graphene research around the world, the National Science Library of the Chinese Academy of Sciences, under the guidance of its Department of Development and Planning, has collaborated with Chemical Abstracts Service (CAS), a division of the American Chemical Society, for this scientific analysis of published graphene research. Using structured content curated from the global scientific literature by CAS scientists
and applying quantitative analysis and text mining methods, this analysis focuses on the overall trends, research topic distribution and evolution, distribution of substance properties and applications, geographic distribution, competitive landscape, and other aspects of global graphene research. This report will be a valuable reference for scientists and decision makers, as well as scientific research managers, policy experts and industrial experts to understand the landscape and trends of this important emerging technology field.
# Table of Contents

**Chapter 1 Introduction** ............................................................................................................. 1  
1.1 Background ......................................................................................................................... 1  
1.2 Research content and methods ......................................................................................... 2  

**Chapter 2 Trends Analysis of Global Graphene Research and Development**  ... 3  
2.1 Overall trend of graphene research.................................................................................... 3  
2.2 Research categories distribution ....................................................................................... 4  
2.3 Research topics distribution and evolution ......................................................................... 7  
  2.3.1 Global research topics distribution .................................................................................. 7  
  2.3.2 Research topics evolution ............................................................................................... 7  
  2.3.3 Emerging terms distribution ........................................................................................... 11  
2.4 Substances and roles in overall graphene research: distribution and evolution  ... 11  
  2.4.1 Overall substance role distribution reported in graphene research .................... 11  
  2.4.2 Main substances and roles distribution reported in graphene research ...... 12  
  2.4.3 Role trends of substances reported in graphene research ............................................. 13  
  2.4.4 Role evolution of emerging substances ......................................................................... 15  
2.5 Important research output countries/regions distribution ................................................. 15  
  2.5.1 Important countries/regions distribution ...................................................................... 15  
  2.5.2 Trends of important countries/regions by year ............................................................. 17
2.5.3 Patent application flow in major countries .......................................................... 18

2.6 Main technology area distribution ........................................................................... 19

2.7 Important organization distribution ......................................................................... 20
  2.7.1 Organization distribution based on papers .......................................................... 20
  2.7.2 Assignee distribution for patents ........................................................................ 24

2.8 Analysis .................................................................................................................... 28

Chapter 3 Trends Analysis in Main Research Area of Graphene ......................... 30
  3.1 Research topics distribution in graphene batteries ............................................... 30
  3.2 Research topics distribution in graphene supercapacitors ................................... 30
  3.3 Research topics distribution in graphene sensors .................................................. 31
  3.4 Research topics distribution in graphene flexible electronics ............................... 31
  3.5 Analysis .................................................................................................................. 32

Chapter 4 Prospects .................................................................................................... 37

Annex Chart of Role Indicators and Their Codes ...................................................... 39
Figure 2.1.1 Papers and patents in graphene research by year ........................................ 3
Figure 2.1.2 Trend prediction of papers and patents in graphene research ....................... 4
Table 2.1.1 Prediction parameters of papers and patents in graphene research .............. 4
Table 2.2.1 Top 10 research categories distribution of papers and patents .................... 5
Figure 2.2.1 Development trend of global research categories ...................................... 6
Figure 2.3.1 Topics distribution of global graphene research ........................................... 8
Figure 2.3.2 Topics distribution of papers and patents in graphene research (before 2009).... 9
Figure 2.3.3 Topics distribution of papers and patents in graphene research (2010-2016) ....10
Figure 2.3.4 Evolution of emerging terms of global papers and patents ....................... 11
Figure 2.4.1 Role distribution of substances reported in graphene research .................. 12
Figure 2.4.2 Main substances and roles distribution reported in graphene research... 13
Figure 2.4.3 Role trends of substances reported in graphene research ......................... 14
Figure 2.4.4 Role evolution of emerging substances in graphene research .................. 15
Figure 2.5.1 Countries/regions distribution in graphene research ............................... 16
Figure 2.5.2 Top 5 countries trends of papers by year ................................................ 17
Figure 2.5.3 Top 5 countries trends of patents by year ............................................... 18
Table 2.5.1 Proportion of papers and patents since 2010 in main countries...................... 18
Figure 2.5.4 Patent application flow in main countries ................................................ 19
Figure 2.5.5 Main technology area distribution by year .......................................... 20
Table 2.7.1 Top 20 organizations in graphene research papers ................................. 21
Table 2.7.2 Top 20 assignees in graphene patents ................................................................. 25
Figure 3.1 Research topics distribution in graphene batteries .................................................. 33
Figure 3.2 Research topics distribution in graphene supercapacitors .................................... 34
Figure 3.3 Research topics distribution in graphene sensors ................................................... 35
Figure 3.4 Research topics distribution in graphene flexible electronics .............................. 36
Chapter 1 Introduction

1.1 Background

Graphene is a crystalline allotrope of carbon with 2-dimensional properties. In 2004, Prof. Andre Geim and Prof. Konstantin Novoselov at The University of Manchester extracted single-atom-thick crystallites from bulk graphite, demonstrated existence of crystal graphene. They were later awarded Nobel Prize in Physics for their work in 2010.

As the thinnest known material at one atom thick, graphene is incredibly strong and possesses excellent mechanical, thermal and electrical properties. Its high flexibility, light transparency, and superior electricity conductivity could lead to revolutionary progress in the diverse fields of semiconductors, photovoltaics, lithium-ion batteries, supercapacitors, electronic sensors and electronic display devices.

The National Science Library, Chinese Academy of Sciences (NSLC) in China collaborated with Chemical Abstracts Service (CAS) in the United States, based on the structured scientific information provided by CAS, to explore the global trends in graphene research and provide a global perspective on the basic graphene research and industrial development.

CAS, a division of the American Chemical Society, headquartered in Columbus, Ohio, has captured summaries and important descriptions of evolving chemical sciences since 1907. Their coverage includes all significant journals, books, dissertations and related disclosures on chemistry and related topics published throughout the world, as well as patents from over 60 patent offices. CAS is the world's largest repository of information on chemistry and related publications. CAS REGISTRY℠ is collection of substance descriptions, which have associated with them a single CAS Registry Number® for each unique substance. Since 1963, over 200 million unique chemical entities have been identified and registered. By May 2017, over 130 million CAS Registry Numbers have been assigned and collected. These include unique
organic and inorganic chemical substances, such as alloys, coordination compounds, minerals, mixtures, polymers and salts, and more than 67 million sequences. Indexing of publications is enabled by electronic workflow from publishers and patent offices, but the intellectual effort is provided by human expert review of each document and curated index entry.

NSLC is the public library service system of the Chinese Academy of Sciences. NSLC functions as the key library nationally for collecting information resources and providing information services in natural sciences, inter-disciplinary fields and high-tech fields for the researchers and students of the Academy and researchers around the country. NSLC is the member of the International Federation of Library Associations and Institutions (IFLA), Electronic Information for Libraries (EIFL), Confederation of Open Access Repositories (COAR) and International Council for Scientific and Technical Information (ICSTI). NSLC, together with other information departments in the Chinese Academy of Sciences, scientists, management experts, policy experts, think tank experts and industrial experts, provides a series of intelligence products designed for the decision making, scientific research and industrial fields.

1.2 Research content and methods

In this report, a data set comprised of 78,756 papers and 23,057 patents (applications) on graphene was studied (collected by CAS on April 5, 2016). CAS indexing for topic, concept, substance, commercial or government entity, source of publication, and various other data entities were used to make comparisons of the information over the timeframe studied for graphene research and subsequent development.
Chapter 2 Trends Analysis of Global Graphene Research and Development

2.1 Overall trend of graphene research

The groundbreaking isolation of graphene for the first time in 2004 sparked a global explosion in graphene research (Figure 2.1.1). Both papers and patents increased rapidly in 2005 and 2006, and then grew remarkably since 2007, especially after 2010. Over 50 percent of papers and patents output were during the last three-year period 2014-2016, when both the number of papers and patents increased year on year, indicating that the basic research and applications of graphene are still in rapid growth.

![Figure 2.1.1 Papers and patents in graphene research by year](image)

The Logistic Model (Figure 2.1.2, Table 2.1.1) identified that the fastest development of patents and papers published was in 2013 and 2014, respectively, and would reach a plateau in 2022 and 2025, when the industrial scale application of graphene would likely be achieved.

---

1 Considering the trend was relatively flat before 2000, only data since 2000 are shown.
Figure 2.1.2 Trend prediction of papers and patents in graphene research

Table 2.1.1 Prediction parameters of papers and patents in graphene research

<table>
<thead>
<tr>
<th>Data type</th>
<th>Growth factor</th>
<th>Maximum value</th>
<th>Maximum year</th>
<th>Midpoint</th>
<th>Actual value by 2015</th>
</tr>
</thead>
<tbody>
<tr>
<td>Papers</td>
<td>0.5040</td>
<td>123904</td>
<td>2025</td>
<td>2014</td>
<td>72982</td>
</tr>
<tr>
<td>Patents</td>
<td>0.7682</td>
<td>28714</td>
<td>2022</td>
<td>2013</td>
<td>23055</td>
</tr>
</tbody>
</table>

2.2 Research categories distribution

The discipline/specialty Sections assigned by CAS to each indexed paper and patent were used in this analysis to give an overview of the research area of graphene. As shown in Table 2.2.1 and Figures 2.2.1, graphene research and development have been heavily concentrated 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 the research and development (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.

Table 2.2.1 Top 10 research categories distribution of papers and patents

<table>
<thead>
<tr>
<th>Sections</th>
<th>Papers and patents (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electric Phenomena</td>
<td>25.92%</td>
</tr>
<tr>
<td>Electrochemical, Radiational, and Thermal Energy Technology</td>
<td>11.23%</td>
</tr>
<tr>
<td>Optical, Electron, and Mass Spectroscopy and Other Related Properties</td>
<td>7.92%</td>
</tr>
<tr>
<td>Surface Chemistry and Colloids</td>
<td>7.32%</td>
</tr>
<tr>
<td>Ceramics</td>
<td>6.30%</td>
</tr>
<tr>
<td>General Physical Chemistry</td>
<td>4.69%</td>
</tr>
<tr>
<td>Biochemical Methods</td>
<td>4.45%</td>
</tr>
<tr>
<td>Plastics Manufacture and Processing</td>
<td>3.53%</td>
</tr>
<tr>
<td>Electrochemistry</td>
<td>2.93%</td>
</tr>
<tr>
<td>Magnetic Phenomena</td>
<td>2.34%</td>
</tr>
</tbody>
</table>
Figure 2.2.1 Development trend of global research categories
2.3 Research topics distribution and evolution

2.3.1 Global research topics distribution

The concepts indexed by CAS to each paper and patent were used in this analysis to explore the topics distribution of over 100,000 papers and patents in graphene research between 1985 and 2016. The topics of graphene papers and patents were clustered into several groups, including the electrical properties research, graphene composite materials, material properties and preparation, polymers, sensors, semiconductor devices, batteries and capacitors (Figure 2.3.1).

2.3.2 Research topics evolution

The evolution of graphene research topics was analyzed based on papers and patents by time slice analysis. Two time windows, 1985-2009 and 2010-2016 (Figure 2.3.2 and 2.3.3, respectively), were examined. Before 2009, graphene research mainly focused on the mechanical and other properties and electrical properties. In contrast, since 2010, graphene research has extended continuously to a diverse range of potential applications, such as batteries, capacitors, semiconductors, and sensors devices.

---

2 Considering the dramatic increase after 2010, the data set was divided into two slices.
Figure 2.3.1 Hot topics distribution of global graphene research
Figure 2.3.2: Topics distribution of papers and patents in graphene research (before 2009).
Figure 2.3.3 Topics distribution of papers and patents in graphene research (2010-2016)
2.3.3 Emerging terms distribution

A distribution analysis of indexed concepts was conducted using the number of concepts and emerging concepts in four periods: 1) before 2009, 2) 2010-2011, 3) 2012-2013 and 4) 2014 and after (Figure 2.3.4, the size of the pie chart is proportional to the number of concepts in the papers and patents and the orange color represents the percentages of emerging terms). While the number of concepts increased remarkably in each of the four periods, the proportion of emerging terms was the largest (45.7%) from 2010-2011, and then decreased from 2012-2013 (38.9%) and after 2014 (29.0%). This phenomenon may indicate that while there has been a rapid growth in graphene research over the past decade, there has not been sufficient technical breakthrough.

![Figure 2.3.4 Evolution of emerging terms of global papers and patents](image)

2.4 Substances and roles in overall graphene research: distribution and evolution

2.4.1 Overall substance role distribution reported in graphene research

Analysis was conducted on the substance roles indexed by CAS in the papers and patents (Figure 2.4.1). Overall, 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 (Nanoscale Substances/Materials); 18.6 percent are PROC (Process), including PEP (Physical, Engineering or Chemical Process) and REM (Removal or Disposal). (Role abbreviations are detailed in the Appendix.)
2.4.2 Main substances and roles distribution reported in graphene research

The roles of main substances in graphene research were analyzed (Figure 2.4.2). The main substances include carbon, graphite, silicon, silica and gold, etc., which roles are Technical or Engineered Material Use, Nanoscale Substances / Materials, Properties, Physical, Engineering or Chemical Process, or Reactant. Looking in more detail, the roles of carbon are mainly TEM (Technical or Engineered Material Use), NAN (Nanoscale Substances/Materials), PRP (Properties), while the main roles of graphite are RCT (Reactant), PEP (Physical, Engineering or Chemical Process), TEM (Technical or Engineered Material Use); the roles of Silicon, silica, gold, copper are mainly TEM (Technical or Engineered Material Use), PEP (Physical, Engineering or Chemical Process), PRP (Properties), and aluminum, nickel, platinum, silver are mainly applied...
in TEM (Technical or Engineered Material Use), PEP (Physical, Engineering or Chemical Process), PRP (Properties), and aluminum, nickel, platinum.

Figure 2.4.2 Main substances and roles distribution reported in graphene research

2.4.3 Role trends of substances reported in graphene research

Time trends of substances roles in graphene research were analyzed (Figure 2.4.3). PRP (Properties) has declined dramatically 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 total, the main roles declined in recent years, while roles in Biological Use, Modifier or Additive Use, Pollutant, Removal or Disposal have become a new focus.
Figure 2.4.3 Role trends of substances reported in graphene research.
2.4.4 Role evolution of emerging substances

Time slice analysis was used to examine the role evolution of emerging substances in graphene research (Figure 2.4.4). Based on the emerging substances, the trends in USES and PROC (Process) have declined in recent years. On the contrary, the trends in PREP (Preparation) and BIOL (Biological Study) indexing have increased over time.

![Figure 2.4.4 Role evolution of emerging substances in graphene research](image)

2.5 Important research output countries/regions distribution

2.5.1 Important countries/regions distribution

The country distribution of the first author affiliation was analyzed (Figure 2.5.1). The top five countries are China (excluding Hong Kong, Macao and Taiwan, similarly hereinafter), United States, South Korea, Japan and India. These countries accounted for 64.3 percent of the global papers.

The distribution of patent applicant countries was also analyzed (Table 2.5.1) with the top five countries are China, South Korea, United States, Japan and Germany. These countries accounted for over 90 percent of the global patents.
Figure 2.5.1 Countries/regions distribution in graphene research
2.5.2 Trends of important countries/regions by year

In respect of the trend of papers (Figure 2.5.2), the United States and Japan published their first paper in 1985 and 1992, respectively. However, the publication output of the United States and Japan increased very slightly since 2010, even declining after 2013. In contrast, the number of papers from China increased dramatically after 2010, even surpassing the United States. The publications from South Korea surpassed Japan since 2010, but increased slightly, similar to India in recent years. In addition, nearly half of the publications from China and South Korea were during 2013-2015.

In respect of the trend of patents (Figure 2.5.3), the United States and Japan applied their first patent in 1997 and 1999, respectively, earlier than China (in 2007) and South Korea (in 2003). However, patents of the United States and Japan began to decline after 2013. In contrast, the number of patents from China grew remarkably since 2007 and increased dramatically especially after 2010, while the number of patents from China shouldered above other countries. Moreover, the total patents after 2010 accounted for 59.06 percent of the global patents. While the patent number of South Korea and Germany declined after 2013, the same as United States and Japan. Although the patents from Japan appeared earlier, the total number of patents and the growth rate fell behind China, United States, and South Korea, obviously.
2.5.3 Patent application flow in major countries

Figure 2.5.4 illustrates the flows of patents from the top five countries (the thickness of the arrow is positively correlated with the proportion of the patents that were applied in different countries) and clearly shows that the majority of patents flew to United States and China. Moreover, although the total number of patents from China are high, only 2.3 percent of Chinese patents are applied in South Korea, United
States, Japan and Germany. In contrast, the ratio 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/companies produced the largest number of patents, most of such patents were applied only in China but not in other countries.

Figure 2.5.4 Patent application flow in main countries

2.6 Main technology area distribution

Analysis of technological areas using IPC (International Patent Classifications) based on the patent data was carried out (Figure 2.5.5). The highest concentrations of technological areas are graphene preparation, composites and batteries.

In the past three years, the IPC C08K0013/06 (Pretreated ingredients) and C09D0007/12 (Other additives), H01M0010/0525 (Lithium batteries) and H01G0011/86 (Capacitors, specially adapted for electrodes) are active, while the number of patents in the IPC H01B0001/04 (Mainly consisting of carbon-silicon compounds, carbon, or silicon), H01B0013/00 (Apparatus or processes specially adapted for manufacturing conductors or cables) are relatively low in the past three years. 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.

Figure 2.5.5 Main technology areas distribution by year

2.7 Important organization distribution

2.7.1 Organization distribution based on papers

In analyzing global graphene research organizations (Table 2.7.1), among the top 20 organizations, eleven organizations are located in China, three from the United States, two from South Korea, two located in Singapore, one in Japan and one in Russia. Eighteen out of the top 20 organizations are universities, while the remaining two are institutes, indicating that graphene research is dominated by universities and institutes.

The major research topics of top 20 organizations revealed that the papers of organizations from China mainly focused on sensors, electronics and photovoltaic, and batteries, while organizations from the United States mainly focused on photoelectric properties, electronic structure, thin film transistors, and semiconductors. Organizations from South Korea focused on capacitors, while the organizations from Japan focused on electric properties.
## Table 2.7.1 Top 20 organizations in graphene research papers

<table>
<thead>
<tr>
<th>Organization Names</th>
<th>Countries</th>
<th>Papers</th>
<th>Type</th>
<th>Year Range</th>
<th>Percentage Last 3 years</th>
<th>Top Terms</th>
<th>Recent Terms</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chinese Academy of Sciences</td>
<td>CN</td>
<td>2,973</td>
<td>Institute</td>
<td>1997 - 2016</td>
<td>45%</td>
<td>Raman spectra; Nanocomposites; Surface structure</td>
<td>Electrolytic polarization; Photothermal therapy; Mammary gland neoplasm</td>
</tr>
<tr>
<td>University of California</td>
<td>US</td>
<td>1,296</td>
<td>University</td>
<td>1994 - 2016</td>
<td>26%</td>
<td>Band structure; Electric conductivity; Raman spectra</td>
<td>Optical instruments; Thin film transistors; Ferroelectricity</td>
</tr>
<tr>
<td>Nanyang Technological University</td>
<td>SG</td>
<td>890</td>
<td>University</td>
<td>2001 - 2016</td>
<td>38%</td>
<td>Raman spectra; Nanoparticles; Surface structure</td>
<td>Transition metal; Encapsulation; Photoluminescence</td>
</tr>
<tr>
<td>Tsinghua University</td>
<td>CN</td>
<td>739</td>
<td>University</td>
<td>1998 - 2016</td>
<td>44%</td>
<td>Raman spectra; Electric conductivity; Chemical vapor deposition</td>
<td>Pore structure; Ion transport; Dielectric films</td>
</tr>
<tr>
<td>Russian Academy of Sciences</td>
<td>RU</td>
<td>738</td>
<td>Institute</td>
<td>1999 - 2016</td>
<td>38%</td>
<td>Electric conductivity; Density of states; Band structure</td>
<td>Lennard-Jones potential; Surface acoustic wave; Magnetocaloric effect</td>
</tr>
<tr>
<td>National University of Singapore</td>
<td>SG</td>
<td>712</td>
<td>University</td>
<td>2000 - 2016</td>
<td>30%</td>
<td>Nanoribbons; Electric conductivity; Raman spectra;</td>
<td>Flexibility; Permeability; Battery electrolytes</td>
</tr>
<tr>
<td>The University of Texas</td>
<td>US</td>
<td>672</td>
<td>University</td>
<td>2004 - 2016</td>
<td>25%</td>
<td>Band structure; Electric conductivity; Field effect transistors</td>
<td>Band offset; Melting point; Raman spectroscopy</td>
</tr>
<tr>
<td>University of Science and Technology of China</td>
<td>CN</td>
<td>616</td>
<td>University</td>
<td>2003 - 2016</td>
<td>41%</td>
<td>Nanocomposites; Nanosheets; Electric conductivity</td>
<td>Phase composition; Atomic layer deposition; Photocatalysts</td>
</tr>
<tr>
<td>Organization Names</td>
<td>Countries</td>
<td>Papers</td>
<td>Type</td>
<td>Year Range</td>
<td>Percentage Last 3 years</td>
<td>Top Terms</td>
<td>Recent Terms</td>
</tr>
<tr>
<td>--------------------</td>
<td>-----------</td>
<td>--------</td>
<td>------</td>
<td>------------</td>
<td>-------------------------</td>
<td>-----------</td>
<td>-------------</td>
</tr>
<tr>
<td>Peking University</td>
<td>CN</td>
<td>563</td>
<td>University</td>
<td>1996 - 2016</td>
<td>44%</td>
<td>Raman spectra; Chemical vapor deposition; Band structure</td>
<td>Superconductivity; Semimetals; Cathodes</td>
</tr>
<tr>
<td>Fudan University</td>
<td>CN</td>
<td>516</td>
<td>University</td>
<td>1994 - 2016</td>
<td>43%</td>
<td>Nanocomposites; Nanosheets; Nanoparticles</td>
<td>Shubnikov-de Haas effect; Chronoamperometry; Crystal orientation</td>
</tr>
<tr>
<td>Zhejiang University</td>
<td>CN</td>
<td>509</td>
<td>University</td>
<td>1997 - 2016</td>
<td>55%</td>
<td>Nanosheets; Raman spectra; Nanocomposites</td>
<td>Open circuit potential; Adsorptive wastewater treatment; Heterojunction solar cells</td>
</tr>
<tr>
<td>Nanjing University</td>
<td>CN</td>
<td>468</td>
<td>University</td>
<td>2002 - 2016</td>
<td>46%</td>
<td>Nanoparticles; Nanocomposites; Surface structure</td>
<td>Crystal morphology; Drug delivery systems; Electrochemical analysis</td>
</tr>
<tr>
<td>Massachusetts Institute of Technology</td>
<td>US</td>
<td>458</td>
<td>University</td>
<td>1989 - 2016</td>
<td>30%</td>
<td>Raman spectra; Chemical vapor deposition; Electric conductivity</td>
<td>Thermoelectricity; Laser heating; Optical conductivity</td>
</tr>
<tr>
<td>Sungkyun-kwan University</td>
<td>KR</td>
<td>446</td>
<td>University</td>
<td>2007 - 2016</td>
<td>50%</td>
<td>Raman spectra; Chemical vapor deposition; Field effect transistors</td>
<td>Double-layer capacitor electrodes; Aerogels; Aminoplasts</td>
</tr>
<tr>
<td>Jilin University</td>
<td>CN</td>
<td>414</td>
<td>University</td>
<td>2008 - 2016</td>
<td>49%</td>
<td>Nanocomposites; Nanoparticles; Surface structure</td>
<td>Lithium-ion secondary batteries; Thermal analysis; Contact angle</td>
</tr>
<tr>
<td>Organization Names</td>
<td>Countries</td>
<td>Papers</td>
<td>Type</td>
<td>Year Range</td>
<td>Percentage Last 3 years</td>
<td>Top Terms</td>
<td>Recent Terms</td>
</tr>
<tr>
<td>-------------------------</td>
<td>-----------</td>
<td>--------</td>
<td>----------</td>
<td>------------</td>
<td>-------------------------</td>
<td>---------------------------------------------------------------------------</td>
<td>----------------------------------------------------------------------------</td>
</tr>
<tr>
<td>Shanghai Jiao Tong University</td>
<td>CN</td>
<td>397</td>
<td>University</td>
<td>2005 - 2016</td>
<td>52%</td>
<td>Nanocomposites; Electric conductivity; Nanosheets</td>
<td>Lithium-ion secondary batteries; Aerogels; Electrochemical reaction catalysts</td>
</tr>
<tr>
<td>Seoul National University</td>
<td>KR</td>
<td>392</td>
<td>University</td>
<td>2004 - 2016</td>
<td>49%</td>
<td>Raman spectra; Surface structure; Electric conductivity</td>
<td>Capacitors; Intercalation; Conducting polymers</td>
</tr>
<tr>
<td>Tohoku University</td>
<td>JP</td>
<td>370</td>
<td>University</td>
<td>1998 - 2016</td>
<td>26%</td>
<td>Band structure; Electric conductivity; Fermi level</td>
<td>Far-IR detectors; Grain size; Hot electrons</td>
</tr>
<tr>
<td>Hunan University</td>
<td>CN</td>
<td>368</td>
<td>University</td>
<td>2001 - 2016</td>
<td>61%</td>
<td>Nanoparticles; Nanocomposites; Cyclic voltammetry</td>
<td>Lithium-ion secondary batteries; Mid-IR spectra; Chemical potential</td>
</tr>
<tr>
<td>Tianjin University</td>
<td>CN</td>
<td>359</td>
<td>University</td>
<td>2003 - 2016</td>
<td>57%</td>
<td>Nanoparticles; Raman spectra; Nanosheets</td>
<td>Lithium-ion secondary batteries; Solar cells; Thickness</td>
</tr>
</tbody>
</table>
2.7.2 Assignee distribution for patents

In analyzing global graphene research assignees (Table 2.7.2), in top 20 patent assignees, 14 assignees were from China, four from South Korea and two from the United States. In addition, the figure indicated that 15 assignees were universities or institutes while the other five were enterprises.

The top five patent assignees were the Chinese Academy of Sciences (1,299 patents), Samsung Electronics Co., Ltd. (515 patents), Ocean’s King Lighting Science & Technology Co., Ltd.³ (439 patents), Zhejiang University (270 patents) and LG Electronics, Inc. (258 patents).

Among the 14 assignees from China, 13 were universities while only one was enterprise. The largest patents output organization in China is the Chinese Academy of Sciences with 1,299 patents.

Among the four assignees from South Korea, two were enterprises while the other two were institutes. The largest patent output organization in South Korea is Samsung Electronics Co., Ltd. with 515 patents. The other three assignees were LG Electronics, Inc., Korea Advanced Institute of Science and Technology (KAIST) and Korea Institute of Science and Technology (KIST).

Two assignees from the United States were International Business Machines Corporation (IBM) and Baker Hughes Inc. The patent applications in South Korea and the United States seem to be dominated by enterprises.

The major research topics of patents from top 20 organizations indicated that the assignees from China applied for patents mainly in preparation, batteries and composites, while the assignees from South Korea applied for patents mainly in semiconductors devices and batteries, the assignees from United States applied for patents mainly in semiconductors devices.

³ This enterprise is a company of lighting technology from China. In this report, the patents of this enterprise were applied during the period 2010-2013. Data since 2014 was not found.
<table>
<thead>
<tr>
<th>Organization Names</th>
<th>Countries</th>
<th>Patents</th>
<th>Percentage Last 3 years</th>
<th>Year Range</th>
<th>Top Terms</th>
<th>Recent Terms</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chinese Academy of Sciences</td>
<td>CN 1,299</td>
<td>Institute</td>
<td>37%</td>
<td>2007 - 2015</td>
<td>Fluoropolymers; Chemical vapor deposition; Films</td>
<td>Three-dimensional printing; Heat stabilizers; Graphene; Films</td>
</tr>
<tr>
<td>Samsung Electronics Co., Ltd.</td>
<td>KR 515</td>
<td>Enterprise</td>
<td>16%</td>
<td>2007 - 2015</td>
<td>Electroluminescent devices; Semiconductor device fabrication</td>
<td>Chalcogenides; Binding energy; Lithium primary batteries</td>
</tr>
<tr>
<td>Ocean's King Lighting Science &amp; Technology Co., Ltd.</td>
<td>CN 439</td>
<td>Enterprise</td>
<td>0%</td>
<td>2010 - 2013</td>
<td>Composite; Secondary batteries; Fluoropolymers</td>
<td>Electrodes; Fluoropolymers; Three-dimensional printing</td>
</tr>
<tr>
<td>Zhejiang University</td>
<td>CN 270</td>
<td>University</td>
<td>49%</td>
<td>2008 - 2015</td>
<td>Composites; Secondary batteries; Lithium-ion batteries; Flexibility</td>
<td>Fluoropolymers; Electrodes; Electric cables and wires; Petroleum pitch</td>
</tr>
<tr>
<td>LG Electronics, Inc.</td>
<td>KR 258</td>
<td>Enterprise</td>
<td>33%</td>
<td>2009 - 2015</td>
<td>Composite; Secondary batteries; Nanocomposites</td>
<td>Fluoropolymers; Electrodes; Polycrystalline hydrogen; Petroleum pitch</td>
</tr>
<tr>
<td>Harbin Institute of Technology</td>
<td>CN 222</td>
<td>University</td>
<td>61%</td>
<td>2010 - 2015</td>
<td>Aromatic hydrocarbons; Polycrystalline hydrogen; Petroleum pitch</td>
<td>Composites; Fluoropolymers; Fluoropolymers</td>
</tr>
<tr>
<td>Tsinghua University</td>
<td>CN 213</td>
<td>University</td>
<td>36%</td>
<td>2009 - 2015</td>
<td>Secondary batteries; Electodes; Fluoropolymers</td>
<td>Cathodes; Electron emission; Fuel cell cathodes</td>
</tr>
<tr>
<td>Organization Names</td>
<td>Countries</td>
<td>Patents</td>
<td>Type</td>
<td>Year Range</td>
<td>Percentage Last 3 years</td>
<td>Top Terms</td>
</tr>
<tr>
<td>--------------------------------------------</td>
<td>-----------</td>
<td>---------</td>
<td>-----------</td>
<td>------------</td>
<td>-------------------------</td>
<td>---------------------------------------------------------------------------</td>
</tr>
<tr>
<td>Shanghai Jiao Tong University</td>
<td>CN</td>
<td>187</td>
<td>University</td>
<td>2009 - 2015</td>
<td>41%</td>
<td>Composites; Secondary batteries; Fluoropolymers</td>
</tr>
<tr>
<td>International Business Machines Corporation</td>
<td>US</td>
<td>186</td>
<td>Enterprise</td>
<td>2005 - 2015</td>
<td>11%</td>
<td>Dielectric films; Field effect transistors; Semiconductor device fabrication</td>
</tr>
<tr>
<td>Korea Advanced Institute of Science and Technology</td>
<td>KR</td>
<td>185</td>
<td>Institute</td>
<td>2008 - 2015</td>
<td>16%</td>
<td>Nanowires; Nanostructures; Nanoparticles</td>
</tr>
<tr>
<td>Southeast University</td>
<td>CN</td>
<td>154</td>
<td>University</td>
<td>2010 - 2015</td>
<td>44%</td>
<td>Composites; Heat treatment; Nanoparticles</td>
</tr>
<tr>
<td>Jiangsu University</td>
<td>CN</td>
<td>140</td>
<td>University</td>
<td>2010 - 2015</td>
<td>54%</td>
<td>Nanocomposites; Photolysis catalysts; Nanoparticles</td>
</tr>
<tr>
<td>University of Jinan</td>
<td>CN</td>
<td>137</td>
<td>University</td>
<td>2010 - 2015</td>
<td>63%</td>
<td>Antibodies and Immunoglobulins; Immunosensors; Blood serum albumins</td>
</tr>
<tr>
<td>Beijing University of Chemical Technology</td>
<td>CN</td>
<td>135</td>
<td>University</td>
<td>2009 - 2015</td>
<td>41%</td>
<td>Styrene-butadiene rubber; Natural rubber; Nanoparticles</td>
</tr>
<tr>
<td>Fudan University</td>
<td>CN</td>
<td>133</td>
<td>University</td>
<td>2010 - 2015</td>
<td>48%</td>
<td>Electrodes; Composites; Lithium-ion secondary batteries</td>
</tr>
<tr>
<td>Organization Names</td>
<td>Countries</td>
<td>Patents</td>
<td>Type</td>
<td>Year Range</td>
<td>Percentage Last 3 years</td>
<td>Top Terms</td>
</tr>
<tr>
<td>--------------------------------------------------------</td>
<td>-----------</td>
<td>---------</td>
<td>-----------</td>
<td>------------</td>
<td>-------------------------</td>
<td>-----------------------------------------------</td>
</tr>
<tr>
<td>University of Electronic Science and Technology of China</td>
<td>CN</td>
<td>130</td>
<td>University</td>
<td>2010 - 2015</td>
<td>36%</td>
<td>Coating process; Films; Polyster</td>
</tr>
<tr>
<td>Shanghai University</td>
<td>CN</td>
<td>129</td>
<td>University</td>
<td>2009 - 2015</td>
<td>62%</td>
<td>Composites; Fluoropolymers; Secondary batteries</td>
</tr>
<tr>
<td>Donghua University</td>
<td>CN</td>
<td>120</td>
<td>University</td>
<td>2010 - 2015</td>
<td>48%</td>
<td>Fluoropolymers; Composites; Polyoxyalkylenes</td>
</tr>
<tr>
<td>Korea Institute of Science and Technology</td>
<td>KR</td>
<td>117</td>
<td>Institute</td>
<td>2008 - 2015</td>
<td>21%</td>
<td>Polymides; Solar cells; Nanoparticles</td>
</tr>
<tr>
<td>Baker Hughes Inc.</td>
<td>US</td>
<td>107</td>
<td>Enterprise</td>
<td>2008 - 2015</td>
<td>12%</td>
<td>Nanoparticles; Fullerences; Silsesquioxanes</td>
</tr>
</tbody>
</table>
2.8 Analysis

1) In recent three years, the numbers of both papers and patents have continued to increase each year, indicating that the basic research and applications of graphene are still in rapid growth.

2) Studies on the functions and properties of graphene are being extended from many aspects. It covers multiple areas such as Electrochemical, Radiational, and Thermal Energy Technology, Optical, Electron, and Mass Spectroscopy and Other Related Properties, Biochemical Methods, Materials Manufacture and Processing, Electrochemistry and so forth. The proportion of research of graphene has increased in recent years in both papers and patents.

3) The development of graphene-based materials and their utilization have largely focused on electrical properties, graphene composite materials, material properties and preparation, polymers, sensors, semiconductor devices, battery materials and capacitors.

4) The industrialized application of graphene materials is continuously deepening and expanding from mechanical and material properties, and electrical properties to a diverse range of potential applications such as batteries, capacitors, semiconductors, sensors devices. The gradual decrease in the proportion of emerging terms in recent years may indicate that technological breakthrough remains to be a significant challenge.

5) The overall studies in graphene and other co-reported substances have focused on applications and preparation processes along with some other aspects. The main substances include carbon, graphite, silicon, silica and gold, etc., which roles are Technical or Engineered Material Use, Nanoscale Substances / Materials, Properties, Physical, Engineering or Chemical Process, Reactant.

In recent years, the usage of some roles has decreased, including Nanoscale Materials, Properties, Industrial Manufacture, Reagent, Catalyst Use, Technical or Engineered Material Use, Analyte, Biological Study, Polymer in Formulation. However, there has been an increasing trend in the usage of the roles in Biological Use, Modifier or Additive Use, Pollutant, Removal or Disposal, indicating a new focus. The roles of emerging substances tend to increase in Preparation and Biological Study over time,
suggesting that the breakthrough in Preparation and Biological Study catches the attention.

6) China, South Korea and United States are competing for the latest application technologies of graphene. The United States and Japan published their papers and applied for patents earlier than China and South Korea. China has become the largest producer of patents and journals in recent years. The majority of patents have been applied in the United States and China. South Korea, United States, Japan and Germany have applied for numerous patents in other countries, whereas China is relatively weak in patent applications in other countries.

7) The technical areas reflected in patents have largely been concentrated in graphene preparation, composite materials and batteries. In the past three years, more areas have been related to the improvement of preparation processes, lithium batteries and capacitors than those related to semiconductors.

8) Although China leads in graphene research and development as indicated by the numbers of papers and patents, most of such efforts are conducted in Chinese universities and institutes. The research and development efforts in South Korea and the United States, on the other hand, are dominated by enterprises. Chinese organizations applied for patents mainly in preparation, batteries and composites, whereas South Korean organizations applied for patents mainly in semiconductor devices and batteries and US organizations applied for patents mainly in semiconductor devices.
Chapter 3 Trends Analysis in Main Research Area of Graphene

As stated in section 2.3 of Chapter 2, the overall graphene research has largely focused on certain technical areas such as electrical properties, graphene composite materials, materials properties and preparation, polymers, sensors, semiconductor devices, battery materials and capacitors. In this chapter, we aim to provide a brief description of the analyses in these four main research areas: batteries, supercapacitors, sensors, and flexible electronics.

3.1 Research topics distribution in graphene batteries

The dataset of graphene flexible electronics includes 8,338 papers and 5,178 patents provided by CAS. Clustering analysis was conducted using indexing concepts (Figure 3.1). The topics are clearly clustered into four groups: 1) secondary batteries: the main research concepts are the polymer materials such as fluoropolymers, carbon fibers, nanofibers, coating materials, alloys, metals and other materials; 2) solar cells: the main research concepts are the electric current potential relationship, photocurrent, photoelectric cell electrodes, thin films, transparent films, band structure, doping, electrodes, and so on; 3) battery anodes: the main research concepts are electrode-related nanomaterials, including nanosheets, nanocomposites, measurement of electric impedance, and electric conductivity, etc.; 4) fuel cells: the main research concepts are fuel cell anodes, surface structure, electrochemical reaction catalysts, nanoparticles, glassy carbon electrode, cyclic voltammetry, electrochemical oxidation and XPS spectra, etc.

3.2 Research topics distribution in graphene supercapacitors

The dataset of graphene supercapacitors includes 3,568 papers and 1,582 patents provided by CAS. Clustering analysis was conducted using indexing concepts (Figure 3.2), with graphene supercapacitors research being mainly focused on the development of electrode materials of supercapacitors. Composition and morphology of electrode materials are usually characterized by X-ray diffraction, X-ray...
photoelectron spectroscopy, scanning electron microscopy, infrared spectroscopy, and other measurements while the electrical properties of electrode materials and supercapacitors are studied by using cyclic voltammetry, constant current charge and discharge, and other electrochemical test methods. Among a variety of electrode materials, polyaniline/graphene composite electrode materials have been substantially studied. In addition, some researches on the preparation processes of supercapacitors have been conducted with main focus on the processes of plates, capacity matching between anodes and cathodes, and other technologies.

### 3.3 Research topics distribution in graphene sensors

The dataset of graphene sensors includes 6,907 papers and 1,623 patents provided by CAS. Clustering analysis was conducted using indexing concepts (Figure 3.3). Biosensors, gas sensors, conductive films and pressure sensors are four important and interesting applications of graphene-based sensors. Graphene-based biosensors can be divided into two categories: 1) electrochemical sensors, using electrochemical signal changes, like current, voltage, etc.; 2) optical sensors, using optical signal changes, such as fluorescence, electroluminescence, chemiluminescence, etc. Applications are mainly for biomedicine (including blood analysis, DNA detection), environmental monitoring (including water analysis and atmospheric monitoring), and food analysis. Moreover, changes of optical and electrochemical signals can be used to develop gas sensors. In addition, graphene-based sensors are also widely used for conductive films and pressure sensors, which can be used to make touch panels, electronic paper in electronic devices, and solar cells.

### 3.4 Research topics distribution in graphene flexible electronics

The dataset of graphene flexible electronics includes 6,882 papers and 1,909 patents provided by CAS. Clustering analysis was conducted using indexing concepts (Figure 3.4). The research topics are divided into five subfields: 1) pressure sensors: the main research concepts include fluoropolymers, polysiloxanes, polyesters, etc.; 2) biological sensors: the main research concepts include proteins, DNAs, chemically
modified electrodes, etc.; 3) field effect transistors: the main research concepts include field effect transistors, electric conductivity, band gap, etc.; 4) semiconductor devices: the main research concepts include semiconductor device fabrication, semiconductor materials, integrated circuits, etc.; 5) transparent conductive films: the main research concepts include transparent films, electroluminescent devices, films, etc.

3.5 Analysis

In graphene battery research, secondary batteries, solar cells, battery anodes and fuel cells are the main topics.

In graphene supercapacitor research, the topics are mainly clustered into electrical properties and electrode materials. Currently, most research is in polyaniline/graphene composite electrode materials.

In graphene sensors research, topics are focused on biosensors, gas sensors, conductive films and pressure sensors. Electrochemical sensors and optical sensors are the major topics for graphene-based biosensors. Applications are focused on biomedical detection including blood analysis, DNA detection, environmental monitoring, including water analysis and atmospheric monitoring, as well as potential applications in food, conductive films and pressure sensors.

In graphene flexible electronics research, topics are focused on field effect transistors, semiconductor devices, transparent conductive films, pressure sensors and biological sensors. Their applications aim to explore transparent conductive property to develop electrical devices, and also to integrate flexible electronics with sensor applications to further expand their potential utilization.
- Secondary batteries
- Battery anodes and nanomaterials
- Solar cells
- Fuel cells and nanomaterials

Figure 3.1 Research topics distribution in graphene batteries
Figure 3.2 Research topics distribution in graphene supercapacitors

- Capacitor electrodes
- Polyamides/graphene composite electrodes
- Manufacturing techniques
- Double layer capacitors
- Electric double-layer capacitance
- Electrical conductivity
- Electrochemical oxidation
- Electrochemical deposition
- Thermogravimetric analysis
- Composite materials
- Nanomaterials
Figure 3.3 Research topics distribution in graphene sensors
Figure 3.4 Research topics distribution in graphene flexible electronics
Chapter 4 Prospects

Graphene, as a rising star in the emerging materials field, has captured attention of scientists, researchers and industry worldwide, and its R&D effort has intensified dramatically since first available in 2004. Studies on the unique combination of superior properties of graphene extend from the basic research of mechanical and electrical properties to the promising applications in batteries, capacitors, semiconductor devices, sensors, polymer-based nanocomposites, etc. The scope of applications will continue to expand, which could open promising markets. Combining all of graphene's amazing properties could create an impact on a scale last seen with the Industrial Revolution. In global competition, China, United States, South Korea and Japan hold the technological advantages in this competitive landscape. In the future, integrating the force of research institutions and enterprises will promote the rapid development of graphene, and even in the face of challenges associated with collaborative work, the promising commercial applications will come true.

Graphene is a promising material in future energy applications due to its unique two-dimensional structure and outstanding electrical, thermal, and optical properties. Given the high level of graphene research in the context of global energy research, its application in the energy field may become one of the fastest growing applications. Graphene as a new energy storage material could facilitate the development of high-performance energy storage devices. Its potential applications in secondary batteries and supercapacitors have increasingly attracted attention from academia as well as industry. Some graphene-containing products are already in trial stage. Meanwhile, as an integral part of the electrode material, graphene has drawn wide attention for its applications in such as solar cells and fuel cells. Related studies are extending from fundamental research to technological applications. In addition, graphene has great prospects as a thermally conductive and heat-dissipating material in the field of thermal management. Graphene also shows attractive application potential in the field of flexible energy devices due to its structural and performance advantages. Research and development of graphene as an electrode material will be the research focus for technological breakthroughs.
Due to graphene’s rapid response to light, electricity, heat, magnetic signals and other signals, studies of graphene-based sensing materials and devices have gradually attracted the attention of researchers in both academia and industry for biological applications. In particular, interest in the potential applications of graphene-based biosensors has emerged for biological detection, physiological monitoring, disease diagnosis, environmental monitoring and food detection. In addition, graphene composite materials are showing great application potential in medical usage such as drug delivery carriers, medical goods, medical repair materials, etc.

As to its application in electronics, because of its transparent conductivity and flexibility, graphene has shown great value in optoelectronics, including smart windows, touch panels, flexible display, flexible lights and so on. Furthermore, graphene-based flexible electronic products can be integrated with flexible intelligent sensors to make flexible smart electronic products, which can be used in intelligent manufacturing, smart wearable products, smart home systems and the internet of things to serve the needs of people’s daily lives. More importantly, graphene-based integrated circuits and semiconductor devices will revitalize the semiconductor industry to produce even more high-tech products.

However, the technology for preparing graphene materials will still be a major focus for future research and exploration. 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. Preparation methods will become more diversified. Development, improvement and optimization of preparation methods and techniques will become a hot research topic for maximizing all aspects of the outstanding performance of graphene. Research will also be focused on the structure anisotropy and performance anisotropy 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 process in order to realize its industrialization for leading innovation in next-generation materials.
## Annex
### Chart of Role Indicators and Their Codes

<table>
<thead>
<tr>
<th>CAS Roles Codes</th>
<th>Specific Roles</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Super Roles</strong></td>
<td><strong>Specific Roles</strong></td>
</tr>
<tr>
<td>ANST (Analytical Study)</td>
<td>AMX Analytical Matrix</td>
</tr>
<tr>
<td></td>
<td>ANT Analyte</td>
</tr>
<tr>
<td></td>
<td>ARG Analytical Reagent Use</td>
</tr>
<tr>
<td></td>
<td>ARU Analytical Role, Unclassified</td>
</tr>
<tr>
<td><strong>BIOL (Biological Study)</strong></td>
<td>ADV Adverse Effect, Including Toxicity</td>
</tr>
<tr>
<td></td>
<td>AGR Agricultural Use</td>
</tr>
<tr>
<td></td>
<td>BCP Biochemical Process</td>
</tr>
<tr>
<td></td>
<td>BMF Bioindustrial Manufacture</td>
</tr>
<tr>
<td></td>
<td>BPN Biosynthetic Preparation</td>
</tr>
<tr>
<td></td>
<td>BSU Biological Study, Unclassified</td>
</tr>
<tr>
<td></td>
<td>BUU Biological Use, Unclassified</td>
</tr>
<tr>
<td></td>
<td>COS Cosmetic Use</td>
</tr>
<tr>
<td></td>
<td>DGN Diagnostic Use</td>
</tr>
<tr>
<td></td>
<td>FFD Food or Feed Use</td>
</tr>
<tr>
<td></td>
<td>NPO Natural Product Occurrence</td>
</tr>
<tr>
<td></td>
<td>PAC Pharmacological Activity</td>
</tr>
<tr>
<td></td>
<td>PKT Pharmacokinetics</td>
</tr>
<tr>
<td><strong>FORM (Formation, Nonpreparative)</strong></td>
<td>GFM Geological or Astronomical Formation</td>
</tr>
<tr>
<td>Category</td>
<td>Type Description</td>
</tr>
<tr>
<td>---------------</td>
<td>--------------------------------------------------------</td>
</tr>
<tr>
<td>OCCU (Occurrence)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>FMU Formation, Unclassified</td>
</tr>
<tr>
<td></td>
<td>GOC Geological or Astronomical Occurrence</td>
</tr>
<tr>
<td></td>
<td>NPO Natural Product Occurrence</td>
</tr>
<tr>
<td></td>
<td>POL Pollutant</td>
</tr>
<tr>
<td></td>
<td>OCU Occurrence, Unclassified</td>
</tr>
<tr>
<td>PREP (Preparation)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>BMF Bioindustrial Manufacture</td>
</tr>
<tr>
<td></td>
<td>BPN Biosynthetic Preparation</td>
</tr>
<tr>
<td></td>
<td>BYP Byproduct</td>
</tr>
<tr>
<td></td>
<td>IMF Industrial Manufacture</td>
</tr>
<tr>
<td></td>
<td>PUR Purification or Recovery</td>
</tr>
<tr>
<td></td>
<td>SPN Synthetic Preparation</td>
</tr>
<tr>
<td>PROC (Process)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>BCP Biochemical Process</td>
</tr>
<tr>
<td></td>
<td>GPR Geological or Astronomical Process</td>
</tr>
<tr>
<td></td>
<td>PEP Physical, Engineering, or Chemical Process</td>
</tr>
<tr>
<td></td>
<td>REM Removal or Disposal</td>
</tr>
<tr>
<td>RACT (Reactant or Reagent)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>RCT Reactant</td>
</tr>
<tr>
<td></td>
<td>RGT Reagent</td>
</tr>
<tr>
<td>USES (Uses)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>AGR Agricultural Use</td>
</tr>
<tr>
<td></td>
<td>ARG Analytical Reagent Use</td>
</tr>
<tr>
<td></td>
<td>BUU Biological Use, Unclassified</td>
</tr>
<tr>
<td>Code</td>
<td>Description</td>
</tr>
<tr>
<td>------</td>
<td>-----------------------------</td>
</tr>
<tr>
<td>CAT</td>
<td>Catalyst Use</td>
</tr>
<tr>
<td>COS</td>
<td>Cosmetic Use</td>
</tr>
<tr>
<td>DGN</td>
<td>Diagnostic Use</td>
</tr>
<tr>
<td>FFD</td>
<td>Food or Feed Use</td>
</tr>
<tr>
<td>MOA</td>
<td>Modifier or Additive Use</td>
</tr>
<tr>
<td>NUU</td>
<td>Other Use, Unclassified</td>
</tr>
<tr>
<td>POF</td>
<td>Polymer in Formulation</td>
</tr>
<tr>
<td>TEM</td>
<td>Technical or Engineered Material Use</td>
</tr>
<tr>
<td>THU</td>
<td>Therapeutic Use</td>
</tr>
</tbody>
</table>

**SPECIAL ROLES:**

<table>
<thead>
<tr>
<th>Code</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>CMB</td>
<td>Combinatorial Study</td>
</tr>
<tr>
<td>MSC</td>
<td>Miscellaneous</td>
</tr>
<tr>
<td>NAN</td>
<td>Nanoscale Substances / Materials</td>
</tr>
<tr>
<td>PPH</td>
<td>Prophetic Synthesis or Use</td>
</tr>
<tr>
<td>PRP</td>
<td>Properties</td>
</tr>
</tbody>
</table>
Consultants Committee

Director: Tao Zhang, Manuel Guzman

Consultants: Keqiang Wang, Chenguang Huang, Zhongfan Liu, Huiming Cheng, Yanfei Ma, Linjie Zhi, Mingming Guo, Gui Yu, Huimin Ma, Yanxia Yin, Guozhen Shen, Lianfeng Sun

Project Planning

Keqiang Wang, Chenguang Huang, Xiangyang Huang, Xiwen Liu, Matthew Toussant, Craig Stephens

Project Coordination

National Science Library: Xiwen Liu, Yajuan Zhao, Xuezhao Wang, Lu Dong

CAS (Chemical Abstracts Service): Michael Dennis, Christine McCue, Caroline Ma, Jinying Zhang, Rhonda Ross, Peter Carlton

Research & Analysis

National Science Library: Li Wang, Lixue Zou, Huifang Xu, Di Zhang, Xiaoli Chen, Xin Chen, Yizhan Li, Dongqiao Li, Yuhan Yang

CAS (Chemical Abstracts Service): Matthew Toussant, Yingqi Wu, Cynthia Liu, Todd Chamberlain, Caroline Ma, Sunny Yu

Data Support

CAS (Chemical Abstracts Service): Matthew Toussant, Yingqi Wu, Cynthia Liu, Todd Chamberlain, Sunny Yu
About Chemical Abstracts Service

CAS, a division of the American Chemical Society, is dedicated to the ACS vision of improving people’s lives through the transforming power of chemistry. The CAS team of highly trained scientists identifies, aggregates, and organizes all publicly disclosed chemistry information, creating the world’s most valuable collection of content that is vital to scientific innovation worldwide. Scientific researchers, patent professionals and business leaders around the world rely on a suite of research solutions from CAS that enables discovery and facilitates workflows to fuel tomorrow’s innovation. Visit the CAS website at www.cas.org.

CAS is located in Columbus, Ohio, USA, with over 1,400 employees.

About National Science Library, Chinese Academy of Sciences (NSLC)

NSLC is the public library service system of Chinese Academy of Sciences. NSLC functions as the key library nationally for collecting information resources and providing information services in natural sciences, inter-disciplinary fields, and high tech fields, for the researchers and students of Chinese Academy of Sciences and for the researchers around the country. NSLC is the member of the International Federation of Library Associations and Institutions (IFLA), Electronic Information for Libraries (EIFL), Confederation of Open Access Repositories (COAR) and International Council for Scientific and Technical Information (ICSTI). NSLC, together with other information departments in Chinese Academy of Sciences, scientists, management experts, policy experts, think tank experts and industrial experts, provides competitiveness T series intelligence products, which design for the decision making, scientific research and industrial fields.