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Science & Technology Trends

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Executive Summary

Life Sciences

1 Syndromic Surveillance — Toward the Early Detection of Infectious Disease Epidemics —

p. 9

In recent years, syndromic surveillance has attracted attention as a new technology that can detect epidemics of man-caused or naturally-occurring infectious diseases in a timely manner and minimize the spread of epidemics. Its development was triggered by the anthrax cases in the United States in 2001 and the SARS outbreak from the end of 2002 to 2003, and it is becoming widespread around the world including Japan. At the core of syndromic surveillance is information on various patient symptoms. It refers to a series of actions-analyzing the gathered information epidemiologically by using statistical methods, making an early judgment as to any outbreaks and epidemics of infectious diseases, notifying health professionals and government organizations of the results, and taking countermeasures against the spread of an epidemic. Compared with diagnosis-based surveillance as seen in the names of diseases such as “influenza” or “measles,” syndromic surveillance is superior in viewpoint of timeliness and flexibility.

In order to promote syndromic surveillance in the future both in Japan and on an international scale, it is necessary to select sources of information on patient symptoms in accordance with objectives, targets, scale, locations and changes in the social environment, without adhering to specific methods or tools, and to constantly explore new information sources and embrace them as necessary. In addition, it is important to select them in a flexible manner and to evaluate their utility and effectiveness at an early date. Furthermore, it is essential to train infectious disease experts who are able to interpret and understand appropriately data obtained from syndromic surveillance and deliver prompt public health responses.

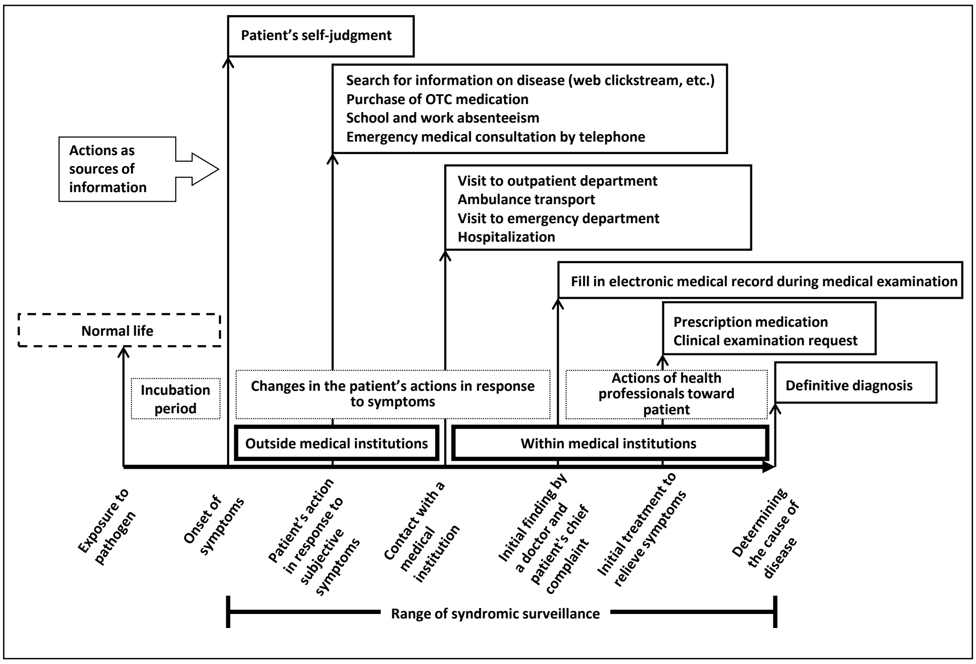

Figure : Sources of Information on Patient Symptoms Subject to Syndromic Surveillance

Prepared by the STFC based on Reference[4]

(Original Japanese version: published in April 2010)

Information and Communication Technologies

2 Trends in R&D in TSV Technology for 3D LSI Packaging

p.26

Computers and other electronic equipment have acquired high-performance features such as smaller sizes, multi functionality or high speed processing by utilizing the high-density LSI integration brought about by the miniaturization through the LSI process scaling. However, there is a limit to extending such miniaturization for technical reasons. The 3D packaging technologies with through-silicon vias (TSVs) are expected to be the key technologies for breaking through the technical limitation. As well as being expected to be one of the packaging technologies replacing high-density integration technologies based on the process scaling, TSV technology has been attracting attention as the key technologies for producing multi-functional LSIs through the packaging together of heterogeneous LSI chips and/or MEMS.

Japan, ahead of other countries, has been carrying out research into the application of TSV technology, and has been the leader in practical product production. However, such research projects and production are still limited, and such research works and products have concentrated on only a portion of the advantages of TSV technology, such as miniaturization or high-density integration. Research organizations all over the world have started research projects aiming at the more sophisticated application of TSV technology through the utilization of all the advantages of TSV technology, including high speed operations, reduced power-consumption, multi-functionality and high-performance. Some of the researches in other countries are even pursuing design methodology innovations.

On the other hand, there still remain a number of technical challenges in various fields, including TSV forming processes, significant related technologies required for applying TSV technology, and design technologies for fully utilizing the advantages of TSV technology.

To tackle such challenges, countries across the world have taken various actions, including kicking-off research projects aiming at industry-relevant applications of TSV technology. Each research project has its own strategy. For example, in US researchers are dedicating themselves to finding industry applications as well as developing essential technologies of TSV adoption. In the EU, new EDA tools are under development and the practical application of TSV technology is being pursued along the long-range landscape of the technology application. The EU, US and Korea associated research consortium is focusing on the test production of TSV based products. The consortium in Japan has been putting its efforts into the improvement of related core technologies leading to realization of market viable products.

To a greater or lesser extent, the above-mentioned research projects have been seeking global alliances, which should attract attention as a keyword in the development of cutting-edge LSI technology.

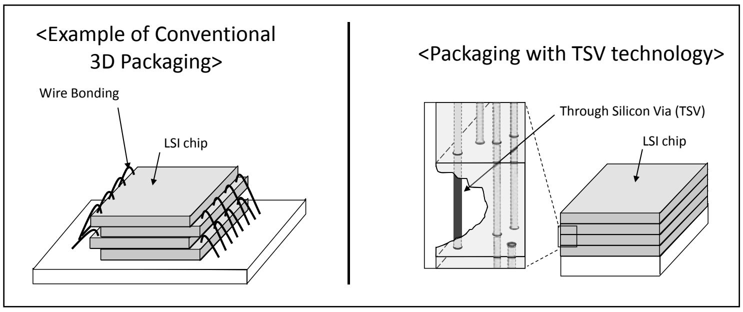

Figure : Comparison of Conventional 3D Packaging and Packaging with TSV technology

Prepared by the STFC

(Original Japanese version: published in April 2010)

3 Promises of Cloud Computing: Underlying Technology That Supports Transformation "From Possession to Utilization"

p.40

Cloud computing represents a series of computations and information processing that are carried out, not by the computing machines at your fingers, but by the computing resources in a cloud computing center located somewhere on the network (i.e. the Cloud), and the results are brought to your display.

The cloud provides various services that functionally correspond to the computer hardware, software, and the programmer's development environment now at your fingers. Its characteristics include the expandability and flexibility of computing resources, elimination of initial investment (charging on an as-used basis), and release of the users from troublesome chores such as maintenance and upgrades.

However, the truly revolutionary character of the cloud computing lies in the fact that it triggers a paradigm shift in information processing engines, i.e. "from possession to utilization." In business communities in particular, the transition of information processing infrastructure from a proprietary to a sharing system involves revolutions in business processes. Along with this revolution, the cloud has the potential to bring about a total reform of industrial structures across the whole spectrum of industries.

At present, Japan does not yet have a world-class cloud center: many challenges call for urgent attention to be paid to dealing with this new technology, including the fostering of an ICT service industry that can take full advantage of the cloud, human resources cultivation, and leaders who can guide society and economy through the adoption of the cloud.

As the cloud computing can have a huge impact on society and industries in general, the information industries see its evolution both with huge expectations and concerns. We will see a drastic reform of business models, and it will trigger a tipping point in Japan's information and telecommunication industry.

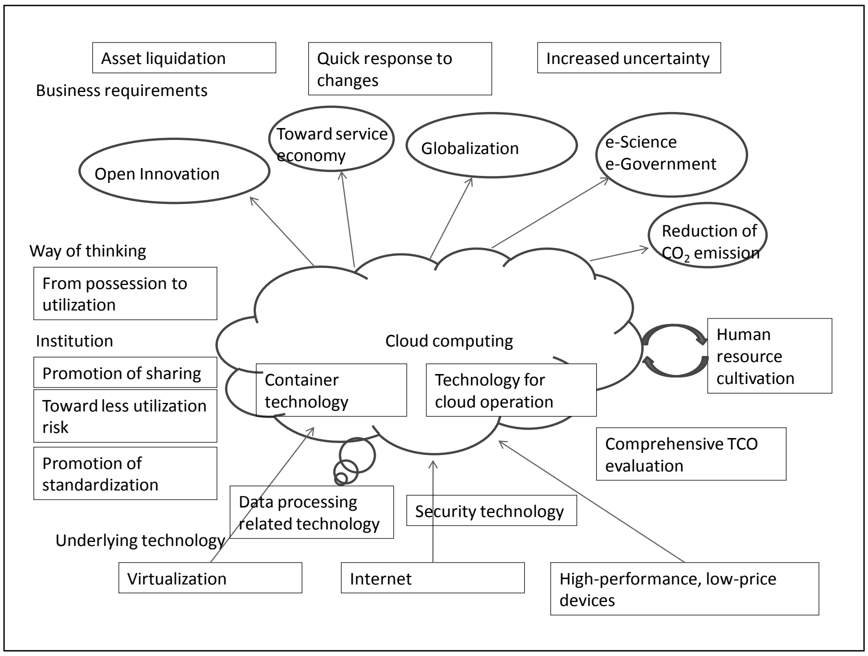

Figure : Environment Surrounding Cloud Computing and Underlying Technologies

Prepared by the STFC

(Original Japanese version: published in June 2010)

Nanotechnology and materials

4 New Trends in Next Generation Biomimetic Material Technology: Learning from Biodiversity

p.53

Since the turn of the century, the research and development on the nature-inspired manufacturing technology, generally referred to as "biomimetics," have been coming to the fore in Europe and the United States. The new functional materials that mimic the peculiar nano/microstructure of insects and plants, deriving various capabilities from them ("the new generation biomimetic materials"), are gaining attention, such as the self-cleaning paint coating that mimics the superhydrophobicity of lotus leaves and the anti-reflective film that mimics moth eyes. The trend is highly expected to go global as they have the potential to sprout "innovation in manufacturing technology," thus promoting new systems of science and technology that are capable of addressing the problems of modern society (i.e., energy, environment, resource, etc.).

The research and development of next generation biomimetics is aiming to solve the problems presented by biology in collaboration with other technologies, such as nanotechnology, and is being strongly pushed ahead especially in Europe. It requires human resource cultivation and network formation, taking place everywhere from museums to a variety of industrial sectors.

The biomimetics research in Japan, on the other hand, has been governed by a "vertically compartmentalized" system that tends to hinder active collaborations among dissimilar areas of science and technology. This situation has held back the research efforts in Japan in simple catch-up and follow-up positions, trying to keep pace with the research examples in Europe and the United States. In order for Japan to construct a new system of science and technology that enables new generation biomimetics research, the following are essential: active promotion of collaboration between dissimilar areas (especially between biology and engineering), organization of a comprehensive support system for joint research, and academic-industrial alliance projects. To lower the barrier that hinders collaborative research efforts, establishment of the framework for human resource cultivation and education is also needed urgently.

(Original Japanese version: published in May 2010)

5 Application of Graphene to High-Speed Transistors: Expectations and Challenges

p.76

Graphene is a single atomic plane of graphite which is one of the layered compounds. Although graphene was discovered very recently, the scope of research has been rapidly expanded because of its distinctive material properties. Especially, its high electron mobility which is 100 times higher than that of silicon has attracted much attention. It is expected to be a material for high speed transistors that would break the operation speed limit of transistors made of conventional semiconductors such as silicon or compound semiconductors.

On the other hand, since the research on graphene is at a very early stage, there are many subjects to be studied intensively for the realization of graphene based devices. One of the most severe problems is that the bandgap is zero, which means that graphene-based transistors would not have a high on/off ratio, and accordingly, that its application to digital devices would not be straightforward. On the other hand, it has already been known that the bandgap of graphene could be made wider through atomic level control of the structure. Control of the structure requires new technologies in film formation, fabrication and assembling, etc., any of which would need to be performed with atomic level precision.

Graphene is a dream material with potential for expanding the horizon of electronic devices. To realize the dream, a wide variety of production technologies are required to be developed.

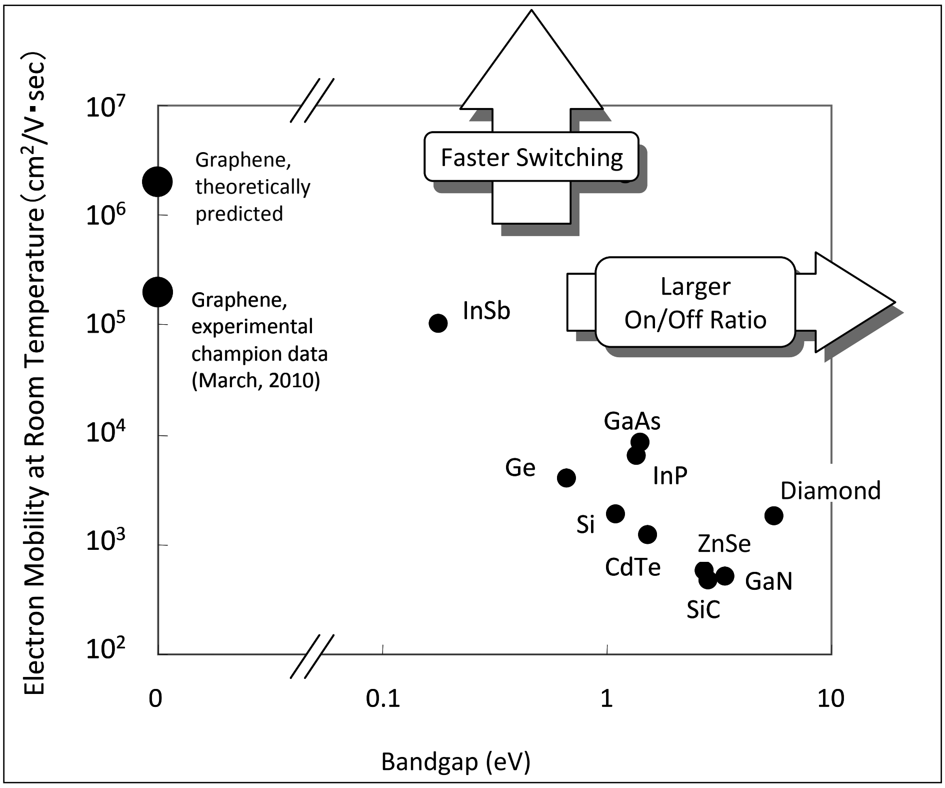

Figure : Electron Mobility and Bandgap of Various Semiconductors

Prepared by the STFC

(Original Japanese version: published in May 2010)

Science & Technology Policy

6 Report on the AAAS Annual Forum (2010) on Science and Technology Policy

p.93

An annual forum of science and technology policy sponsored by the American Association for the Advancement of Science (AAAS) was held in Washington D.C. on May 13 and 14, 2010. The forum is held every year to provide science and technology researchers with an occasion to discuss priority issues, such as policy topics confronting the science community and university research institutes and budget request priorities for the next fiscal year. Participants in this year's forum, which was the 35th of its kind, exchanged views on such topics as "What should the United States do to remain a leader in innovation?," "How to evaluate societal impacts of science and technology," and "What roles can science and technology play in national security issues?" in addition to R&D budget requests for fiscal 2011 and their policy backgrounds.

John Holdren, President Obama's science advisor, made a keynote speech, as he did last year. In the speech, Holdren introduced President Obama's views that science and technology is the key player in domestic and global policy issues and that it is necessary not only to aim at "practical application" science and technology but also to strengthen cross-sectional science and technology infrastructure. He stressed that in order to solve problems it is necessary to establish partnerships across sectors and countries, not to mention among relevant government agencies. He also briefed important issues that have been actively addressed by the Obama administration, including focused budget appropriations for science and technology and the American Innovation Strategy, which President Obama announced in September 2009. With regard to the innovation strategy, Holdren said that basic research and STEM (science, technology, engineering and mathematics) education are building blocks and that promotion of competitive markets to create innovation and catalyst action to break through national priority issues are pillars of the strategy. As for climate change issues, Holdren stated that the government, while stressing the importance of cost-benefit performance, has been promoting the strategy from the standpoint that it is "not energy and climate policy versus the economy" and that it is "energy and climate policy for the economy."

Although R&D budget requests for fiscal 2011 were slashed by 0.3% from the previous year to $148.1 billion, many government agencies saw their budgets increased, including the National Ocean and Atmosphere Administration (NOAA), the National Institute for Standards and Technology (NIST), and the National Aeronautics and Space Administration. Budget requests for basic research increased 4.3% and those for nonmilitary research increased 5.9%. Some participants also raised questions concerning the national debts that have accumulated due to huge fiscal deficits.

The latest forum can be characterized by the fact that discussions were focused on how to achieve accountability for the effect of investments, to which President Obama paid utmost consideration, and for the role played by science and technology in policy and social issues, and on how to steer science and technology by forging solid footing. In the United States, enhancing education remains a big challenge, especially in the primary and secondary stage of education, and it is positioned as a basic component in the context of creating innovation. Discussions at the forum revealed that the government has been making efforts to that end, with the active participation of the science community.

(Original Japanese version: published in June 2010)

1

Syndromic Surveillance — Toward the Early Detection of Infectious Disease Epidemics —

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1 Introduction

Infectious disease epidemics are one of the major crises faced by human society. Following the outbreak of diseases such as SARS (severe acute respiratory syndrome), an emerging infectious disease that shook the world from the end of 2002 to 2003, and the pandemic (H1N1) 2009, cross-border health crisis management has become more important. Mainly in Asia, avian influenza A (H5N1) infection in humans is still being reported, and emerging infectious disease epidemics is of concern.

The early detection of infectious disease outbreaks in order to minimize the spread of epidemics is central to countermeasures against the diseases. In recent years, "syndromic surveillance" has attracted attention as a new technology that meets these demands. The word "surveillance" is generally used when surveying trends in infectious diseases or the economy. It refers to the systematic collection, analysis and interpretation of data required for the planning, implementation and evaluation of countermeasures against diseases, through continuous monitoring of the situation and trend of disease occurrence, enabling the establishment of effective countermeasures based on the results of prompt and regular surveillance feed back to stakeholders.

Syndromic surveillance focuses on patient symptoms such as fever, diarrhea and vomiting. As syndromic surveillance spends less time than the diagnosis-based surveillance, it is said to enable the early detection of infectious disease epidemics and the taking of prompt measures to prevent their spread. In a situation where the "improvement and enhancement of surveillance" come at the top of the list of countermeasures against emerging and reemerging infectious diseases, including new influenza subtypes, discussed at international conferences hosted by the World Health Organization (hereinafter referred to as WHO), expectations for syndromic surveillance are high.

In syndromic surveillance, technology to analyze information on patient symptoms epidemiologically using statistical methods, as well as technology for the efficient collection, processing and distribution of the information, play an important role. While allowing details of those technologies to be discussed in other reports, this article focuses on the positioning of syndromic surveillance in countermeasures against infectious diseases in humans, describes research and development trends and practical application examples in Japan and abroad, and extracts future challenges.

2 What is Syndromic Surveillance?

2-1 Definition and Objective

Research and development and practical applications of syndromic surveillance have been promoted since the anthrax cases following the 9-11 terrorist attacks in the United States in 2001, as well as the SARS outbreak from the end of 2002 to 2003, with the aim of developing anti-bioterrorism measures and the early detection of epidemics of emerging and reemerging infectious diseases-in particular, unknown or rare diseases. With regard to the operation of syndromic surveillance, the U.S. Centers for Disease Control and Prevention (hereinafter referred to as the U.S. CDC) proposes the following definition as the most comprehensive and most accepted today[1]:

Syndromic surveillance is "an investigational approach where health department staff, assisted by automated data acquisition and generation of statistical alerts, monitor disease indicators in real-time or near real-time to detect outbreaks of disease earlier than would otherwise be possible with traditional public health methods."

In other words, syndromic surveillance is "an action that captures outbreaks of disease in real-time or near real-time by focusing on symptoms that serve as disease indicators, collecting information automatically and analyzing the information epidemiologically using statistical methods."

According to the Japanese Ministry of Health, Labour and Welfare's description of syndromic surveillance in its guidelines for measures against new influenza subtypes, syndromic surveillance is "a surveillance for the early detection of outbreak of an infectious disease, through the identification of rapid increases in patients with the target disease based on the number of patients with specified symptoms prior to a diagnosis confirmation from a physician".[2] The Infectious Disease Surveillance Center of the National Institute of Infectious Diseases describes syndromic surveillance as "a surveillance of 'symptoms' with the aim of promptly engaging in the 'early detection' of epidemics of emerging and reemerging infectious diseases-in particular, unknown or rare diseases",[3] a description which explains the objective of syndromic surveillance.

When the above points are taken together, it can be said that syndromic surveillance is "to collect information on patient symptoms, analyze the information epidemiologically by using statistical methods, make an early judgment as to any outbreaks and epidemics of disease, notify health professionals and government organizations of the results, and take early public health measures," and "an effective action for preventing the spread of epidemics of man-caused (caused by bioterrorism) or naturally-occurring infectious diseases."

2-2 Types

At the core of syndromic surveillance is information on patient symptoms. Symptoms vary, from fever to coughing, rashes, diarrhea, vomiting, and spasm. Patient symptoms are collected extensively, using as sources of information about outpatient visits, emergency department visits, medication sales, school and work absenteeism, and ambulance transportation. A worker, for example, wakes up one morning and feels unwell, so he takes his temperature and finds that it is just over 37ºC. He buys and takes over-the-counter medication (hereinafter referred to as OTC medication)[NOTE 1] such as antipyretics and a combination cold remedy at the pharmacy on his way to work and during his lunch break, and sees how he feels for the day while continuing to work. After he comes home, he checks the flu epidemic situation on the Internet. When his temperature goes up the next day, he takes a day off work and visits a doctor. His symptoms get worse quickly, and he cannot go to a medical institution by himself due to severe vomiting and diarrhea, so he is transported by ambulance and is hospitalized. Syndromic surveillance focuses on each behavior that becomes evident with such progression of a patient's symptoms, and uses this as the information source for the collection of information on many patients' symptoms.

Figure 1 shows examples of the sources of information on patient symptoms in syndromic surveillance.[4] Naturally, these actions of a patient or health professionals are not unique to infectious diseases, and can be observed in other diseases. Specifically, it is conceivable that many people might develop similar symptoms to those described above in a short period of time due to food poisoning, toxic gas or radiation exposure. Therefore, in order to determine whether a symptom is caused by an infectious disease and to make a final judgment as to the occurrence of an epidemic, it is necessary to check the syndromic surveillance results against the diagnosis-based surveillance results (see also 2-3).

Syndromic surveillance is divided into cases where surveillance is based on information sources from medical institutions and cases where it is based on other information sources. Information sources of the former type include outpatient and emergency department visits, and surveillance using these sources consists of collecting information on the outpatients' subjective symptoms and objective symptoms (symptoms that can be observed by the doctor, such as a rash, jaundice or bleeding) at the clinic, counting the number of patients for each specific symptom, and analyzing the information epidemiologically (this is referred to as syndrome surveillance for outpatient visits). In syndromic surveillance for outpatient visits, electronic medical records are being

[NOTE 1] : OTC (over-the-counter) medication
medication that is available at pharmacies, drugstores, etc. without a prescription. The term derives from the way a pharmacist hands medication to a patient over the counter at pharmacies and drugstores.

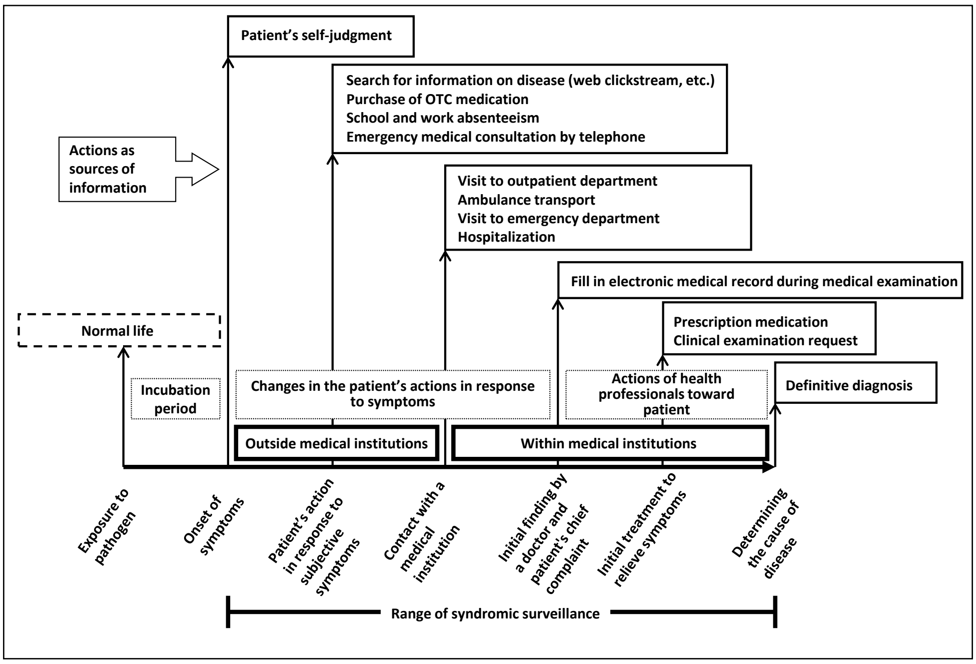


Figure 1 : Sources of Information on Patient Symptoms Subject to Syndromic Surveillance

Prepared by the STFC based on Reference[4]

Table 1 : Major Types of Syndromic Surveillance

	Type	Surveillance target
Within medical institutions	Surveillance for outpatient visits	Number of outpatients for each specific subjective and objective symptom (fever, coughing, vomiting, diarrhea, rash, etc.), counted based on patients' answers to the doctor's questions during their visit to an outpatient or emergency department and the doctor's observations
	Surveillance for prescription medication	Number of out-of-hospital prescriptions of specific therapeutic classifications processed at pharmacies (antipyretics, painkillers, antibiotics, Tamiflu, Relenza, etc.)
	Surveillance for ambulance transport	Number of transported patients (by symptom) based on records of ambulance dispatches
Without medical institutions	Surveillance for OTC medication sales	Sales of OTC medication at pharmacies and drugstores (by type of medication, such as combination cold remedy)
	Surveillance for school absenteeism	Number of people absent from school (by symptom)
	Surveillance for internet search	Number of searches for specific key words (e.g.: Influenza)

Prepared by the STFC

used increasingly in recent years in order to collect information on patient symptoms efficiently (see also 2-5). Other information sources from medical institutions include prescriptions (out-of-hospital prescriptions) processed at dispensing pharmacies, ambulance transportation and hospitalization. On the other hand, information sources of the latter type include OTC medication sales and school and work absenteeism, as well as Internet searches for influenza information, which have attracted attention as a new source of information. The major types of syndromic surveillance based on the information sources described above are shown in Table 1.

While attempts have been made to carry out various types of syndromic surveillance up to now, multiple types of surveillance are often conducted concurrently at the practical application stage following verification tests for each type. For measures against bioterrorism and the pandemic (H1N1) 2009 to be described in chapter 3, several types of syndromic surveillance are conducted concurrently and, based on the results, a comprehensive judgment is made as to the occurrence of an infectious disease epidemic.

Meanwhile, it has been reported that the usage frequency of each type of syndromic surveillance varies depending on each country's medical practices. According to a questionnaire survey of U.S. public health departments, of the syndromic surveillance types shown in Table 1, surveillance for outpatient visits, and in particular, surveillance for emergency department visits, was conducted the most frequently.[5] The survey showed that

84% of the 43 public health departments conducting syndromic surveillance have introduced surveillance for emergency department visits. This was followed by surveillance for outpatient department visits (49%), surveillance for OTC medication sales (44%), and surveillance for school absenteeism (35%) (as of 2007). The cost of the maintenance of syndromic surveillance, according to responses from 18 health departments, ranged from 5,500 dollars to 1,000,000 dollars (median of 95,000 dollars), varying widely among institutions. The survey was conducted by the International Society for Disease Surveillance (ISDS) in 2007. Between August 2007 and February 2008, 59 U.S. public health departments nationwide funded by the U.S. CDC through its cooperative agreement for emergency preparedness were surveyed, of which 52 responded (a response rate of 88%). Of the 52 health departments that responded, 43 reported having experience of conducting syndromic surveillance.[5]

2-3 Comparisons with Diagnosis-based Surveillance

The characteristics of syndromic surveillance can be understood well when compared with those of diagnosis-based surveillance. Diagnosis-based surveillance is based on the names of diseases diagnosed by a doctor, such as “influenza” or “measles.” It has been used for many years in international surveys of infectious disease outbreaks led by WHO and national surveys in the public health administration by various countries. In the case of Japan, the surveillance of infectious disease patients provided in the “Law Concerning the Prevention of Infectious Diseases and Medical Care for Patients with Infections” (Law No. 73, last revised as of June 18, 2008; hereinafter referred to as the Infectious Disease Control Law) falls under this category (this is called an “Trend survey on infectious disease outbreaks”). Since it is based on a definitive diagnosis, it offers superior reliability but poor timeliness and flexibility.

By contrast, syndromic surveillance excels in timeliness as it was developed in order to detect infectious disease epidemics at an early stage. In addition, as it involves information on patient symptoms, investigations are possible even in cases where the name of the disease has not been determined. Even unknown infectious diseases can be detected if any symptoms are present, indicating a high level of flexibility. However, while syndromic surveillance can suggest the possibility of an epidemic of some kind of infectious disease, it cannot determine the actual disease. In addition, since fever, coughing and gastrointestinal symptoms are not unique to infectious diseases, there is a risk of capturing a mass outbreak of diseases other than infectious diseases (see also 2-2). In terms of reliability, therefore, syndromic surveillance is inferior to diagnosis-based surveillance.

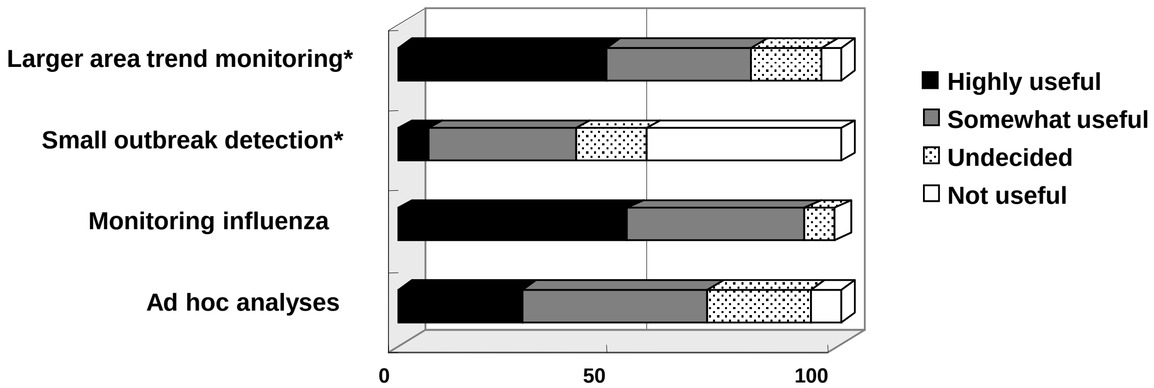
The two types of surveillance described above are mutually complementary from the three standpoints of timeliness, flexibility and reliability. When taking measures against infectious diseases, it is essential that syndromic surveillance is conducted hand in hand with diagnosis-based surveillance.

2-4 Utility and Effectiveness

The utility and effectiveness of syndromic surveillance, in reality, are likely to be largely affected by the public health management systems of each country or region. However, there are few reports of systematic analysis methods which measure the utility value of syndromic surveillance and their results. Here, I will refer to part of the results of the questionnaire survey of U.S. public health departments described in 2-2 as an example that demonstrates the practical capability of syndromic surveillance (Figure 2).[5]

Looking at Figure 2, in terms of monitoring larger areas and monitoring influenza, 80% and 92% of the respondents, respectively, reported that syndromic surveillance was “highly useful” or “somewhat useful.” This indicates that U.S. public health departments evaluate highly the utility of syndromic surveillance in monitoring larger areas and monitoring influenza. On the other hand, their evaluations of syndromic surveillance for small outbreak detection were low. The ratings were similar for areas with four years or more of experience in conducting syndromic surveillance and those with fewer years of such experience. Therefore, it is likely that the results reflect the intrinsic adequacy of syndromic surveillance, regardless of the amount of skill required.

The utility and effectiveness of syndromic surveillance also differ depending on the types of syndromic surveillance described in Table 1. While various evaluations are available, here, the findings based on a report by Yan et al. are summarized in Table 2.[6] Since the advantages and weaknesses in



* "Larger area" refers to city, county, or state, and "small outbreak detection" refers to detecting events within families, nursing homes, day care centers, or geographic areas defined by a postal zip code.

Figure 2 : Results of Questionnaire Survey of U.S. Public Health Departments on the Utility of Syndromic Surveillance

Prepared by the STFC based on Reference[5]

Table 2 : Characteristics of Each Syndromic Surveillance Type

	Specificity*	Timeliness*	Advantages	Weaknesses
Surveillance for outpatient visits (outpatient and emergency departments)	High	Medium to High	Routinely generated; often available in electronic format	Difficulty of searching keywords of symptoms (due to misspellings and abbreviations, deletions of negative words, and vocabulary differences across medical institutions for the same symptoms)
Surveillance for OTC medication sales	High to Medium	High	Providing early signs and indications more timely than patient visits; data routinely generated and available in electronic format	Additional information about medication purchasers is unknown (inquiry and investigation after a symptom has been found are difficult)
Surveillance for school or work absenteeism	Low to Medium	High	Timely	Lack of disease characterization

* These are comparisons among syndromic surveillance types indicated in the left column, not comparisons with surveillance based on definitive diagnosis.

Prepared by the STFC based on Reference[6]

the table are provided from a feasibility perspective, please check against the operation overview described in 2-5 below with respect to surveillance for outpatient visits.

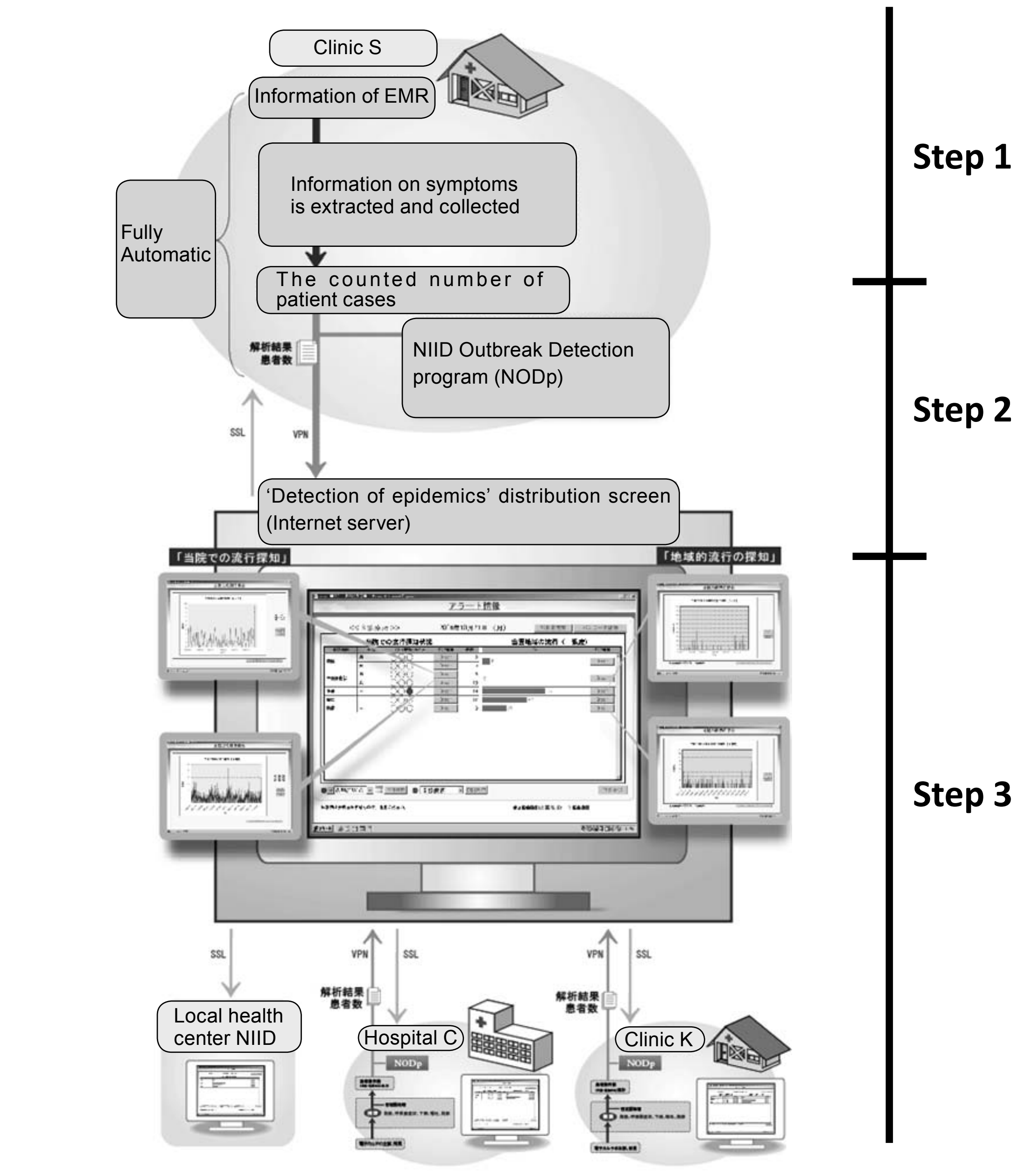
2-5 System Organization and Operation Overview

The operational process of syndromic surveillance consists of three steps: 1) selecting the information source of symptoms and collecting information; 2) analyzing the collected information and, based on the results, judging the likelihood of an infectious disease epidemic; and 3) notifying health professionals and government organizations in charge of measures against infectious diseases of the result of 2). These steps are common to all types of syndromic surveillance.

However, since infectious disease epidemics come in various forms depending on the microbiological characteristics of pathogens and the environment of the outbreak area, and since syndromic surveillance utilizes various information sources, the information collection and analysis algorithms are diverse. The main objective of basic research on syndromic surveillance is to establish these algorithms, and various research findings have been reported in Japan and abroad.

In the following, I will outline the operations involved by taking the example of surveillance for outpatient visits under trial operation by the National Institute of Infectious Diseases (Figure 3).[7]

In the example of Figure 3, information is collected for symptoms of fever, respiratory symptoms such as coughing and breathing difficulties, diarrhea, vomiting, and rashes. In Step 1, information on these symptoms is extracted and collected from medical data entered in the electronic medical records of designated medical institutions. If the information on symptoms is stored in text format in electronic medical records, words describing symptoms can be extracted by using the full text search function.



NIID: National Institute of Infectious Diseases, EMR: Electronic medical records

Figure 3 : System Chart of Syndromic Surveillance for outpatient visits
Source: Infectious Disease Surveillance Center, National Institute of Infectious Diseases[7]

If symptom words are included, they are extracted as one patient case. The removal of negative words is important; for example, in the case of fever, by processing negative phrases such as "fever: none," "no fever," "no fever either," and "fever (-)," only those patients who have the symptom are counted. Patient data other than symptom information are limited to age and gender, and other information that leads to the identification of the individual, such as name, address and health insurance card number, are not collected. Furthermore, information collection and extraction are conducted within the medical institution, and only the data of the counted number of patient cases are used for analysis in the following steps. Thus, this operational process is based on the concept of personal information protection.

In Step 2, the collected data are analyzed. Figure 3 uses an analysis program developed in basic epidemiological research.[8] Based on various past infectious disease outbreak trends, this program sets past epidemic patterns as a baseline by applying a multivariate analysis that adds seasonal and day-of-the-week factors (it also takes into consideration whether the day falls after a holiday). Cases where the number of patients who have actually developed symptoms is significantly higher than the baseline are considered abnormal and are indicated in three alert levels: low, medium and high. As can be seen from the program, the objective of this analysis is to detect at an early stage epidemics that deviate from past infectious disease epidemic patterns. Explained in terms of a specific infectious disease, the annual epidemic of seasonal influenza, for example, is not considered an abnormal infectious disease epidemic as it does not show deviations from past epidemic patterns.

In Step 3, only the number of patients obtained in Step 1 and the alert information obtained in Step 2 are automatically extracted and sent to an Internet server. The number of patients, alert information and epidemic detection information gathered in the server are posted on the website. The system developed by the National Institute of Infectious Diseases uses a VPN (Virtual Private Network) for data transmission and reception, and an SSL (Secure Socket Layer) for sending out information.

After Step 3, based on the epidemic detection information described above, public health department officials will judge whether to collect more detailed information and, in some cases, will make inquiries at medical institutions. Depending on the response to the inquiry, concrete action may follow, such as local institutes of health taking patient specimens and conducting microbiological examinations. If further epidemics are confirmed, the relevant government organizations will take steps to prevent a spread of the epidemic, such as issuing requests to refrain from using and operating public transport and from holding meetings. Since these judgments and measures cannot be automated, it is necessary to seek the judgment of infectious disease experts.

3 Research and Development of Syndromic Surveillance and Attempts toward Its Practical Application : Domestic and International Developments

Here, I will introduce research and development of syndromic surveillance and practical examples in Japan and abroad, and consider its utility and effectiveness with respect to measures against infectious diseases.

3-1 Global Trends

Research and development in syndromic surveillance was triggered by the anthrax cases following the 9-11 terrorist attacks in the United States in 2001, as well as the SARS outbreak from the end of 2002 to 2003. Furthermore, WHO's revised International Health Regulations (hereinafter referred to as IHR2005), which entered into force in June 2007, require timely reporting and action in the event of public health emergencies of international concern, including infectious disease epidemic and mass outbreaks of disease caused by chemicals and radioactive materials,[9] and expectations of syndromic surveillance are growing as a way of meeting this requirement.

By country, efforts being made in the United States toward practical applications are prominent. Yan et al. reviewed about 200 publications released between 1997 and 2006, and found that 12 syndromic surveillance systems, including the U.S. CDC's BioSense and EARS (Early Aberration Reporting System), and RODS (Real-time Outbreak and Disease Surveillance), run jointly by the University of Pittsburgh and Carnegie Mellon University, were reported as nationwide-level syndromic surveillance systems as of 2008.[6] According to the nationwide questionnaire survey conducted by Lori et al. in the United States in 2009 (to which 41 of the 50 states responded), of the above systems, the most widely adopted system was BioSense (20.61%), followed by RODS (13.39%).[10] At local and state levels, 18 syndromic surveillance system implementations, such as projects run by New York City and the State of Michigan, have been reported.[6]

Syndromic surveillance in the United States, overall, is mainly aimed at fighting bioterrorism. Following the above-mentioned anthrax cases in 2001, a nationwide campaign against bioterrorism has been implemented, based on the Public Health Security and Bioterrorism Preparedness and Response Act of 2002, and Biodefense for the 21st Century, a homeland security executive order issued in April 2004. In the latter executive order, in particular, "Surveillance and Detection" is one of the pillars of the biodefense program, and practical application of syndromic surveillance has been promoted as part of efforts to improve relevant systems. Additionally, in recent years, syndromic surveillance applications have expanded to include measures at state, local and city levels against norovirus infection, which is raising concerns about an epidemic in the United States, as

Table 3 : Major National and International Syndromic Surveillance Systems (Except the United States and Cases in 3-2 and 3-3)

	Surveillance	Responsible body	Network	Surveillance target
National level	QSurveillance®	British Health Protection Agency, Egton Medical Information Systems Ltd., University of Nottingham	Over 3,000 practices nationwide (as of 2009)	Influenza-like symptoms, respiratory symptoms, gastrointestinal symptoms, etc.
	French Syndromic Surveillance System	French Institute for Public Health Surveillance (Institut de Veille Sanitaire, InVS)	98 hospitals in France and four overseas departments (OSCOUR Network; as of 2007)	Influenza-like symptoms, respiratory symptoms, and gastrointestinal symptoms
	Alternative Surveillance Alert Project (ASAP)	Health Canada	Canadian Association of Chain Drug Stores (CACDS) member stores	Sales of antidiarrheal and antinausea OTC medication (gastrointestinal symptoms)
	Australian Sentinel Practices Research Network (ASPREN)	Royal Australian College of General Practitioners (RACGP), University of Adelaide	More than 100 general practitioners nationwide (as of 2009)	Influenza-like symptoms,gastrointestinal symptoms and other specific symptoms
	Emergency Department Information System in Korea	Korea Centers for Disease Control and Prevention (Korea CDC)	125 sentinel hospitals (as of 2008)	Acute respiratory symptoms
	Taiwan's Respiratory Syndromic Surveillance System (RSSS)	Centers for Disease Control (Taiwan) (Taiwan CDC)	189 hospitals (as of 2005)	Influenza-like symptoms, respiratory symptoms, etc.
International level	Early Warning Outbreak Recognition System (EWORS)	U.S. Naval Medical Research Unit Two (NAMRU-2)	Public health departments and medical institutions of Indonesia, Cambodia, Vietnam, Laos and South Korea	Symptoms of infectious disease registered in ICD*1 or arbitrarily-found symptoms
	DiSTRIBuTE (Distribute Syndromic Surveillance Project)	International Society for Disease Surveillance (ISDS)	U.S. CDC, U.S. Public Health Informatics Institute (PHII), Markle Foundation	Influenza-like symptoms
	SIDARTHa (the Emergency Data-based System for Information on, Detection and Analysis of Risks and Threats to Health)	European Commission co-funded project (June 2008 - December 2010)	Public health departments and medical institutions of 12 European countries (project group), as well as an advisory body comprising officials of the European Centre for Disease Prevention and Control (ECDC) and WHO	Influenza-like symptoms and symptoms of other infectious diseases

*1 The International Classification of Diseases (ICD), recommended by the WHO, was first created in 1900 in order to establish an international standard of classification for causes of death, and has since been revised approximately every 10 years (the latest is ICD-10). “Certain infectious and parasitic diseases” are registered and are classified into intestinal infectious diseases, tuberculosis, sepsis, viral hepatitis, human immunodeficiency virus (HIV) disease and other diseases.

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well as measures against new influenza subtypes. National, local and state public health departments are conducting multiple syndromic surveillance systems concurrently to make a comprehensive judgment on the occurrence of an infectious disease epidemic.

Other than the United States, practical applications or trial operations of syndromic surveillance have been launched in the UK, Canada, South Korea, Taiwan, Australia, France, Japan, etc. Like the United States, they have conducted various syndromic surveillance systems with the chief aim of fighting bioterrorism, new influenza subtypes, and infectious diseases that present gastrointestinal symptoms such as norovirus infection. Examples of syndromic surveillance as anti-bioterrorism measures that have been published in implementation reports and academic papers include: the G8 Hokkaido Toyako Summit in Japan in July 2008; U.S. President Barack Obama’s visit to Japan in November 2009; the FIFA World Cup held in Japan and South Korea from May to June 2002; and the G8 summit in Gleneagles, Scotland, in July 2005. Table 3 summarizes syndromic surveillance systems other than those related to anti-bioterrorism measures (except for the United States and cases described in 3-2 and 3-3). These are conducted at national or international levels.

Most syndromic surveillance systems are run by government organizations in charge of public health management and national research institutes, or jointly conducted between those organizations and universities. A certain degree of involvement from government organizations is considered to be necessary in order to take steps as promptly as possible, based on the results of syndromic surveillance, to prevent the spread of an infectious disease epidemic, such as issuing requests to refrain from using and operating public transport.

3-2 Syndromic Surveillance for prescription medications and School Absenteeism

In the following, I will refer to cases of syndromic surveillance conducted in Japan during the pandemic (H1N1) 2009 outbreak and analyze how the surveillance led to the early detection of the epidemic. I will also evaluate the consistency of the results between syndromic surveillance and diagnosis-based surveillance. Furthermore, I will introduce surveillance for Internet search as an example of recently developed syndromic surveillance. While syndromic surveillance, as described previously, is used widely as an anti-bioterrorism measure, this article, instead of referring to cases based on hypothetical infectious disease epidemics, will look at cases of infectious disease epidemics that actually occurred.

In April 2009, a new influenza subtype, whose outbreak was first reported in Mexico, spread rapidly across the world and, on June 12, 2009. WHO raised its alert level to Phase 6, the pandemic phase. Since an influenza pandemic is believed to occur in 10- to 40-year cycles from past cases of the Spanish flu, Asian flu and Hong Kong flu, WHO member countries had prepared an action plan for countermeasures even before the pandemic (H1N1) 2009.

In Japan, the Pandemic Influenza Preparedness Action Plan was formulated by the Inter-ministerial Avian Influenza Committee in December 2005, followed by the enforcement in May 2008 of the Law on Partial Revision of the Law Concerning the Prevention of Infectious Diseases and Medical Care for Patients with Infections and the Quarantine Act (Act No. 30 of 2008). The amended law created a new classification called "Pandemic human influenza and relevant infections," enhancing surveillance systems for a possible influenza pandemic. The above action plan, revised in February 2009, places great importance on the role of syndromic surveillance[11]: "It is extremely important to detect an outbreak of new influenza subtype as early as possible through surveillance, and prevent the spread of infection to minimize damage."

During the pandemic (H1N1) 2009 outbreak in Japan, syndromic surveillance was put to practical use by the National Institute of Infectious Diseases. The institute had been conducting research and development in surveillance for outpatient visits, ambulance transport, prescription medication, OTC medication sales, and school absenteeism prior to the pandemic as measures against various public health crises of international concern required by IHR2005 (FY2007-FY2009; "Empirical study on early detection of local health crisis management information and information sharing systems including government organizations" as part of a multidisciplinary research project on health and safety crisis management measures under the health science and labour research grant from Ministry of Health, Labour and Welfare; research representative Dr. Yasushi Ohkusa). As part of the research and development effort, surveillance systems for prescription medication and school absenteeism attributable to new influenza subtype were established and their effectiveness and utility were tested during the pandemic H1N1 2009 outbreak (as of March 2010, both of the surveillance systems are in progress).

Surveillance for prescription medication, as described in Table 1, is based on the number of prescriptions issued for each specific therapeutic classification. In Japan, the out-of-hospital prescription rate exceeds 50% and the computerization rate of dispensing pharmacies is high. The out-of-hospital prescription rate was 59.3% in a 2008 survey (2008 Social healthcare survey by medical action; Social Statistics Division, Statistics and Information Department, Minister's Secretariat, Ministry of Health, Labour and Welfare), and the computerization rate of dispensing pharmacies stood at 98.9% as of July 2009 (the Trend of Medical Care Expenditures Pharmacies (Pharmacies dispensing expenditures); Actuarial Research Division, Health Insurance Bureau, Ministry of Health, Labour and Welfare). By using prescription data, information on many patients can be obtained and, since the data are mostly computerized, automatic data collection is possible.

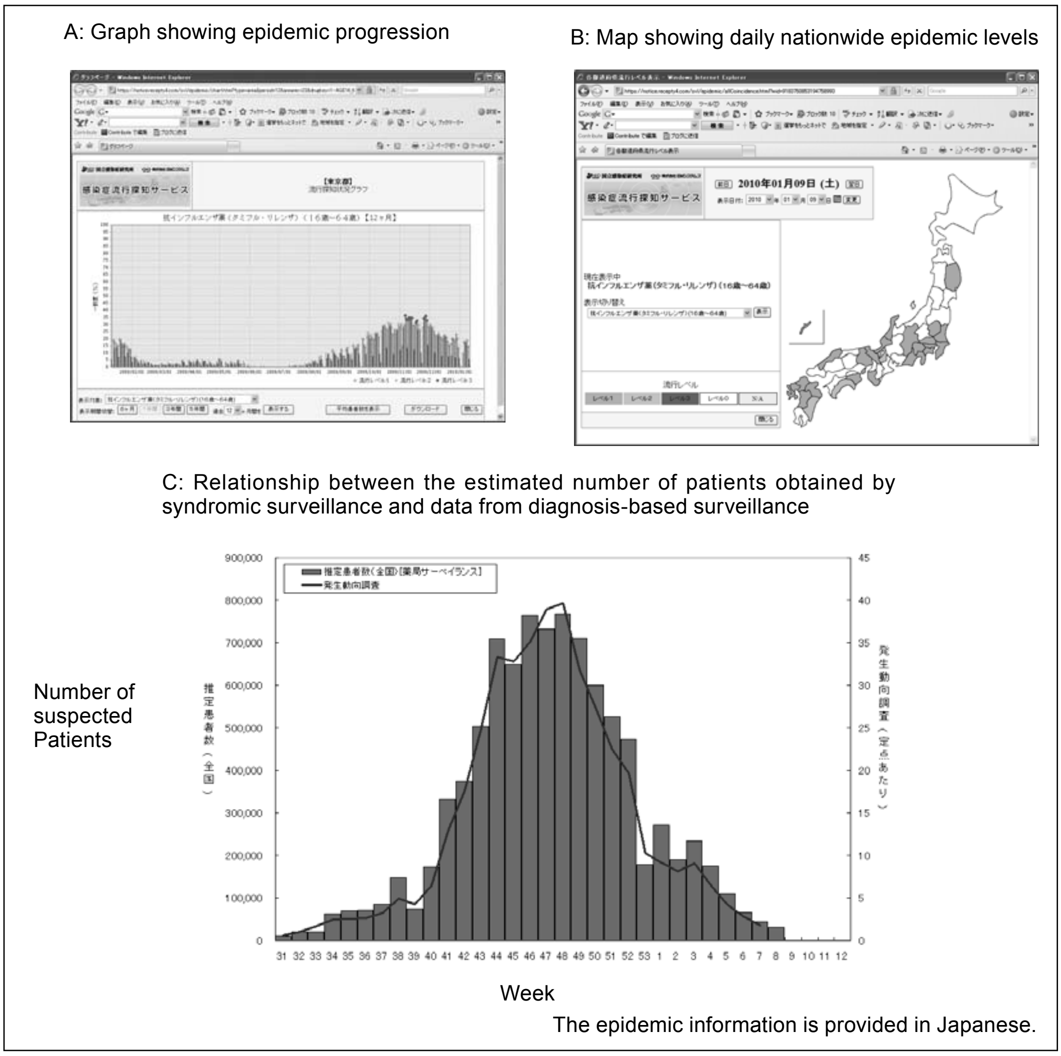

Figure 4 : Information Provided in Surveillance for prescription Medication

Source: Infectious Disease Surveillance Center, National Institute of Infectious Diseases[12]

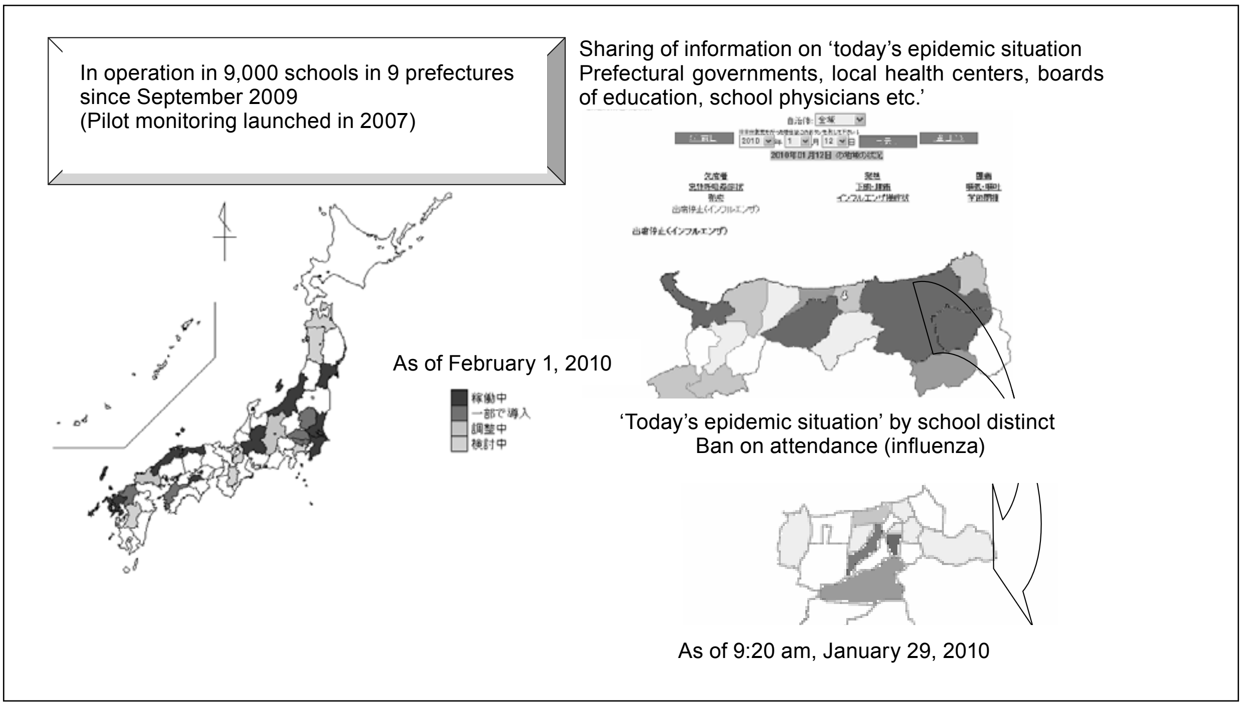

Figure 5 : Information Provided in Surveillance for School Absenteeism

Source: Infectious Disease Surveillance Center, National Institute of Infectious Diseases
(Group conference material pertaining to the research project of Reference[13])

When the therapeutic classification of antiviral drugs for influenza is selected, for example, the number of prescriptions will correspond one on one to the number of suspected influenza patients, thus it is likely to provide a highly accurate surveillance result. Surveillance for prescription medication as a countermeasure against the pandemic (H1N1) 2009 has been conducted in earnest by the National Institute of Infectious Diseases since April 20, 2009. Specifically, the number of prescriptions of, mainly, Tamiflu® and Relenza®, both antiviral drugs for influenza, is being monitored at 4,042 pharmacies nationwide (as of April 10, 2010; equivalent to approximately 9% of all pharmacies in Japan) that gathers out-of-hospital prescription data by ASP (Application Service Provider). The monitored data are distributed to health professionals next day in the form of information collection and analysis results. Thus, it can be said that this enables almost real-time detection of an infectious disease epidemic. Figure 4 shows examples of information distributed to health professionals.[12]

According to the results up to the end of December 2009, 38 prefectures reported a high positive correlation between the estimated number of patients obtained by surveillance for prescription medication and the actual number of patients obtained from diagnosis-based surveillance (a correlation coefficient of 0.9 or higher). These results have led to an evaluation that the surveillance conducted was able to present indicators of the pandemic (H1N1) 2009 ahead of diagnosis-based surveillance.[13]

Meanwhile, the National Institute of Infectious Diseases has conducted surveillance for school absenteeism in earnest since September 2009.[13] In the surveillance for school absenteeism, the absenteeism situation of all students suffering from fever, headaches, acute respiratory symptoms, diarrhea and abdominal pain, nausea and vomiting, rashes, and influenza-like symptoms were monitored in a total of 9,000 elementary, junior high and high schools, equivalent to 19% of all schools in Japan (covering nine prefectures as of February 2010) (Figure 5).

In January 1-15, 2010, a questionnaire survey of participants in the surveillance for school absenteeism was conducted. Responses were obtained from 2,218 respondents including school officials, board of education officials and public health department officials of local governments, and views such as on the usefulness of surveillance in making a decision on temporary school closures were heard.[13] However, the FY2009 project report notes that there remain problems in the surveillance system for school absenteeism (see also 4-2).[13] It seems that it will be necessary to examine further the intrinsic effectiveness and utility of surveillance for school absenteeism through future research and development and verification tests.

3-3 Surveillance for Internet Search

In recent years, surveillance of seasonal influenza that utilizes Internet search information has attracted attention. Such systems enabling the early detection of seasonal influenza epidemics in the United States were made public in 2008 by the University of Iowa and other U.S. academic institutions and Yahoo! Research,[14] and by Google.org and U.S. CDC.[15] The former used search query logs in the United States from March 2004 through May 2008 and demonstrated that the number of searches containing the terms "influenza" or "flu" was strongly linked to the percentage of influenza-positive cases in clinical tests and death attributable to pneumonia and seasonal influenza. In other words, they found a positive correlation between the number of influenza-related searches and the number of patients who actually displayed symptoms of seasonal influenza. Based on this result, Google.org developed a more comprehensive and automated Internet search surveillance system, and released an experimental version of Google Flu Trends on November 11, 2008 (U.S. local time; the same shall apply hereinafter) (available in Japan by the service name of "Influ-trend").[16] It has been reported that, whereas the U.S. CDC's traditional Influenza Sentinel Providers Surveillance Network takes one to two weeks for information collection, analysis and publication of results, the two systems described above are able to process information faster. In other words, by analyzing the number of search query data related with influenza, it is possible to estimate an epidemic of seasonal influenza prior to a definitive diagnosis.

Google Flu Trends[16] is similar to the Internet search surveillance system of the University of Iowa et al. in that they are both based on influenza-like illness (ILI)-related search queries. However, Google Flu Trends covers a wider variety of search terms (according to Ginsberg et al., 45 queries related to influenza complications and remedies were established at the initial stage of system development),[15] divides the epidemic level into five phases, and shows the estimated epidemic level by means of maps by country or by region and temporal transitional graphs. In particular, in deciding on the epidemic level, Google Flu Trends compares the estimates based on search data against a historic baseline level of influenza activity for that area. Data are updated on the Internet on a daily basis, and Google Flu Trends releases visualized information on the seasonal influenza epidemic situation in almost real-time. In addition, Google Flu Trends verifies estimated data from each country by using diagnosis-based surveillance data officially released by the respective public health management institutions.

With regard to the handling of personal information, Google.org says "we are keenly aware of the trust our users place in us, and of our responsibility to protect their privacy. Google Flu Trends can never be used to identify individual users because we rely on anonymized, aggregated counts of how often certain search queries occur each week."

The effectiveness of Google Flu Trends has been demonstrated by comparisons with data from the above-mentioned traditional influenza surveillance conducted by the U.S. CDC. Ginsberg et al.[16] compared the data from weekly reports on the proportion of patients suffering from influenza-like symptoms in nine U.S. regions over five years (2003-2007) with estimated data obtained from Google Flu Trends, and found that the two showed a strong positive correlation (a correlation coefficient of 0.80-0.96). In addition, when surveillance using Google Flu Trends was conducted in the same nine regions on a trial basis during the seasonal influenza epidemic in 2007-2008, Google Flu Trends reportedly succeeded in detecting the epidemic one to two weeks earlier than the U.S. CDC's data release. Furthermore, in New Zealand, it has been reported that the peak period for the seasonal influenza epidemic in 2009 was indicated by Google Flu Trends one week earlier than reports from general practitioners.[17]

Google Flu Trends, only available in the United States when first launched in November 2008, has since extended its coverage to countries such as Mexico, New Zealand and Australia, adding Japan and certain European countries on October 8, 2009, and covering a total of 20 countries as of March 2010.

4 Issues Regarding Future Development

As shown in Figure 1 and Table 2, syndromic surveillance has a broad information source and an extensive coverage area. It can be conducted at national or international levels and, as in the U.S. case described in 3-1, it can be conducted at local, state and city levels within a country. In addition, as shown in Table 2, differences in utility and effectiveness have been reported depending on the type of syndromic surveillance. Here, I will attempt to capture syndromic surveillance in its entirety and identify what is required for the future development of domestic and international syndromic surveillance systems.

4-1 Issues Common to All Systems

As described in Chapter 3, syndromic surveillance has been conducted worldwide in recent years, and the types of syndromic surveillance have become increasingly diverse. With such widespread use, however, various issues with regard to syndromic surveillance systems have also been pointed out.

Chretien et al., responsible for the U.S. Department of Defense Global Emerging Infections Surveillance and Response System (DoD-GEIS), raised four important issues-1) technical, 2) financial, 3) political, and 4) ethical, social and cultural considerations-in building syndromic surveillance systems.[18] In the following, issues will be extracted in line with these considerations.

From technical and financial perspectives, the key is to collect information on patient symptoms as efficiently and effectively as possible to maintain the operation of syndromic surveillance systems. While issues regarding information collection, analysis and distribution technologies and cost-related issues vary depending on the surveillance target, location and system, there is room for improvement, in particular, with regard to software. Chretien et al., referred to above, has proposed the introduction of open-source software to replace the commercial software used in many existing syndromic surveillance systems in order to reduce operational costs.[19] The proposed software should be compatible with various information sources and be equipped with a function that can automatically collect, analyze and distribute data. In other words, since a high level of usability is required, software developers and persons conducting syndromic surveillance need to collaborate for software creation.

From a political standpoint, coordination between administrative departments of national and local governments, as well as cooperation with stake holders, is important. In the case of Japan, the National Institute of Infectious Diseases, quarantine stations, local institutes of health, local health centers, medical institutions, and organizations involved with the information sources of each syndromic surveillance system need to work closely together to build a framework for syndromic surveillance, under jurisdiction of the departments of national and prefectural governments in charge of public health administration, school health administration, and occupational health administration.

With respect to ethical, social and cultural issues, greater public understanding of syndromic surveillance as a countermeasure against infectious diseases is necessary. In particular, understanding with regard to information disclosure is crucial. While syndromic surveillance is based on personal and medical information regarding symptoms, information that can identify the individual is not released from institutions that possess the information source. Persons responsible for conducting syndromic surveillance are obliged to be accountable to the public in adhering to the privacy policies of syndromic surveillance. In addition, when building syndromic surveillance systems, it is also necessary for the public to cooperate in maintaining the flexibility of such systems by refraining from overestimating or underestimating specific methods and tools. Google Flu Trends, for example, is gaining worldwide recognition and is prospective for a useful countermeasure against infectious diseases; in Japan, however, public awareness of medical services serves as a hurdle to its full-scale introduction. Considering the differences between Japan and other countries in their outpatient care systems, internet search patterns of Japanese people may not always be the same as those of people from other countries. It is necessary to select information sources and verify systems by keeping in mind that the utility and effectiveness of syndromic surveillance may vary according to its location and social influences. In the following, I will describe more specific issues concerning Japan.

4-2 Domestic Issues

In Japan, several syndromic surveillance systems have been developed mainly by the National Institute of Infectious Diseases and are at the stages of experimental demonstration, trial operation and practical application. The following are issues that have been highlighted through conducting syndromic surveillance.

From a technical standpoint, the need for further consideration with respect to the compatibility of data management software has been pointed out in surveillance for outpatient visits and ambulance transport (sourced from group conference materials pertaining to the research project of Reference[13]). The two current surveillance systems have been developed for software for specific electronic medical records or records of ambulance dispatches, and are not compatible with software that differs among medical institutions or fire departments. With respect to electronic medical records, in particular, there are cases where different software systems are used at different medical institutions or, in university hospitals, at different departments, and technological development is required to enable the necessary information to be extracted from the various software systems. To this end, cooperation is needed among the National Institute of Infectious Diseases, which is leading surveillance efforts, medical institutions and vendors of electronic medical records. In addition, since information collection is not automated in the current surveillance system for school absenteeism, the school needs to enter data for each event of absenteeism. According to Ohkusa et al.,[13] an average of 7-8 minutes is reportedly required for entering data under the current system, and further technological development is necessary in the future to reduce the operation.

In view of their future widespread use, national and local governments should consider measures to incorporate surveillance for prescription medication and school absenteeism, which are at the practical application stage, into public health administration at an early date. Also, in surveillance for outpatient visits, the widespread use of electronic medical records is essential. According to the Ministry of Health, Labour and Welfare's survey of medical facilities (static survey), as of 2008, electronic medical records were introduced in the entire facility in 10.8% (948 facilities) of hospitals and 13.1% (12,939 facilities) of clinics. While the figure rose 5.6% for hospitals and 6.8% for clinics from the results of the same survey three years ago,[19] the situation is far from being ready for conducting a full-scale operation of syndromic surveillance. The New IT Reform Strategy compiled by the government's Strategic Headquarters for the Promotion of an Advanced Information and Telecommunications Network Society (IT Strategic Headquarters) calls for the widespread use of electronic medical records and other medical information systems in order to improve the quality and efficiency of medical services.[20] Thus, the spread of electronic medical records is also desirable from the perspective of contributing to improving the quality of medical services as a whole through countermeasures against infectious diseases.

Meanwhile, with regard to surveillance for school absenteeism, it is hoped that verification of its utility and effectiveness will make progress through future verification tests. Sites where group activities take place, such as schools, are prone to become hotbeds for infectious diseases and, at the same time, may trigger a spread of the epidemic to the home and the community. It is considered to be meaningful, from the perspective of public health management, to measure the utility value of surveillance for school absenteeism.

4-3 International Issues

Expectations for syndromic surveillance are growing with respect to international public health measures promoted by IHR2005. IHR2005 calls for an enhancement of measures against large-scale infectious diseases, irrespective of whether they are man-caused or naturally-occurring.[9]

In considering measures against emerging infectious diseases, it is particularly important to conduct syndromic surveillance in Africa's tropical regions, Asia and Latin America where infectious diseases are epidemic frequently. Public health infrastructure is generally underdeveloped in these areas, and they typically lack the experimental facilities for clinical research and tests. Therefore, in many cases it is difficult to conduct diagnosis-based surveillance, and syndromic surveillance would become an effective measure against infectious diseases. In introducing syndromic surveillance, it is necessary to minimize the costs of installing and maintaining a surveillance system by making use of low-cost netbook PCs, mobile phones, and smartphones as a means of the collection, processing and distribution of information. At the same time, it is important to ensure that conducting syndromic surveillance does not interfere with existing medical systems. Creating community-based syndromic surveillance programs and seeking the participation of volunteers equipped with public health knowledge should be considered so as not to place an excessive burden on the limited number of medical staff. The consideration of syndromic surveillance systems that involve lower financial burdens and do not waste human resources are under way, and trial surveillance cases of malaria, food-borne infectious diseases and sexually transmitted diseases are being accumulated in the above-mentioned areas.[21]

In order to disseminate syndromic surveillance globally in the future, including in the above-mentioned areas, it is necessary to make greater use of the syndromic surveillance skills in developed countries and existing achievements of international syndromic surveillance. It is desirable to strengthen the network of experts of WHO and the International Society for Disease Surveillance (ISDS), and to provide venues for exchanging views and information on ways to overcome technical, financial, political, ethical, social and cultural issues. In order to advance Asia's public health management system as a whole, Japan needs to deepen further its partnership with WHO's Western Pacific Regional Office (WPRO) and the Asia-Pacific Economic Cooperation (APEC), and take action such as being more active in providing the above-mentioned venues for exchanging views and information.

5 Other Important Perspectives

Syndromic surveillance offers superior timeliness and flexibility than diagnosis-based surveillance. While its timeliness is obvious considering its primary objective, its flexibility is noteworthy in that it can also accommodate unknown infectious diseases since the name of the disease is not required. In addition, the diversity of syndromic surveillance systems should also be noted. Various information sources are available for capturing a patient's symptoms, and the utility and effectiveness of syndromic surveillance change depending on the information source and the surrounding social environment. The expected outcome of syndromic surveillance is also diverse. Surveillance for outpatient visits, by linking information on infectious diseases with that on other diseases through the use of electronic medical records, is considered to be useful for improving the quality of medical services as a whole. Conducting syndromic surveillance on sites of group activities such as in schools is expected to improve public health knowledge, understanding and management skills within the local community to which the site belongs. Furthermore, Internet search surveillance is considered to contribute to enhancing Internet users' awareness of the public health situation at national and international levels. In general, since syndromic surveillance is diverse, the required approach is to select the information source in accordance with the objective, target, scale, location and changes in the social environment, without adhering to specific methods or tools, and to constantly explore new information sources and embrace them as necessary. Considering the need to select valuable information sources rationally among a wide variety of sources, I would like to emphasize that the flexible selection of information sources and a swift evaluation of their utility and effectiveness are the two key points of promoting syndromic surveillance.

While the National Institute of Infectious Diseases is taking the initiative in conducting syndromic surveillance in Japan, it is desirable that other related research institutes, private organizations and enterprises also take part at the system development stage. With regard to the National Institute of Infectious Diseases, which has led efforts in organizing syndromic surveillance systems, analyzing information, making a comprehensive judgment and taking public health responses to prevent the spread of epidemics, a further enhancement of its role is required in the future.

While this article discusses syndromic surveillance for humans, it is also necessary to look at monitored data of animals in the future when considering measures against emerging infectious diseases. This is because it has been reported that more than 60% of emerging infectious diseases are zoonotic infections.[22] Syndromic surveillance for humans should be promoted with the aid of data regarding

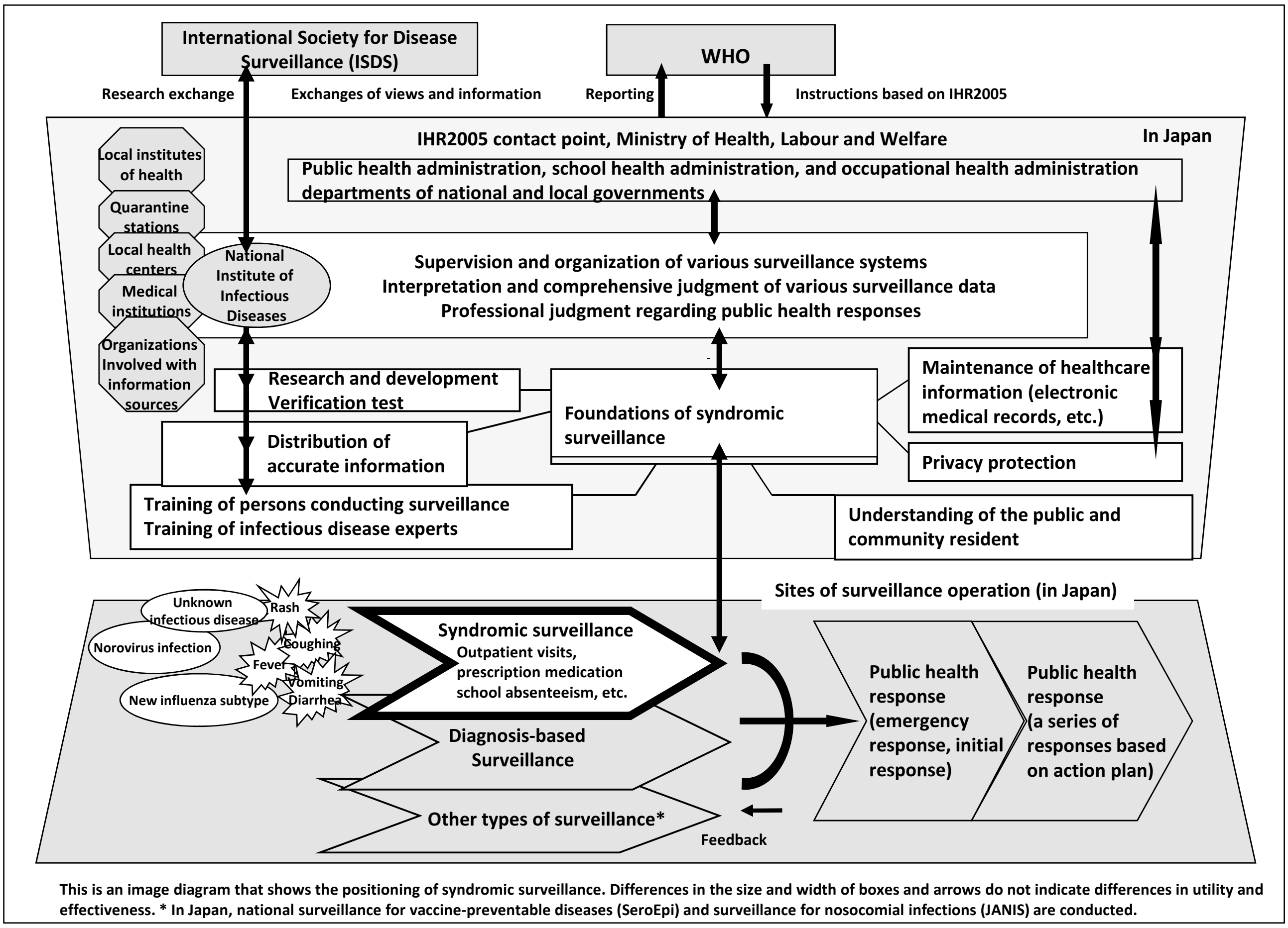

Figure 6 : Framework for Syndromic Surveillance in Japan

Prepared by the STFC.

behavioral abnormalities, diseases and mass deaths of migratory birds, arthropods, wild mammals and livestock.

Figure 6 sums up the positioning of syndromic surveillance among measures against infectious diseases as a whole as well as its future framework, and it is clear that syndromic surveillance is applied at a very early stage. While it is considered to be possible to fully automate the information collection, analysis and distribution operations of syndromic surveillance in the future, human judgment is necessary for taking concrete measures to prevent the spread of an epidemic based on that information. In other words, it is essential to train infectious disease experts who are able to interpret and understand data obtained from syndromic surveillance appropriately and swiftly prompt public health-related responses.

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References

[1] Henning KJ, Overview of syndromic surveillance. What is syndromic surveillance? MMWR Morb Mortal Wkly Rep 53 (Suppl): 5-11 (2004).

[2] Ministry of Health, Labour and Welfare, Expert meeting on pandemic influenza, Guideline for the Surveillance of Pandemic Influenza (From Phase 4 Onwards) (March 26, 2007): http://www.mhlw.go.jp/bunya/kenkou/kekkaku-kansenshou04/pdf/09-e03.pdf.

[3] Infectious Disease Surveillance Center, National Institute of Infectious Diseases, Syndromic surveillance: http://www.syndromic-surveillance.net/syndromic/index.html. [in Japanese]

[4] Mandl KD et al., Implementing syndromic surveillance: A practical guide informed by the early experience. JAMIA 11: 141-150 (2004).

[5] Buehler JW et al., Syndromic surveillance practice in the United States: Findings from a survey of state, territorial, and selected local health departments. Advances Dis Surveill 6: 3 (2008).

[6] Yan P et al., Syndromic surveillance systems: Public health and biodefense. Annu Rev Inform Sci Tech 42 (2008).

[7] Tamie Sugawara et al., Development of automatic syndromic surveillance for infectious diseases using electronic medical record . Iryo Johogaku 28: 13-20 (2008) [in Japanese].

[8] Yasushi Ohkusa et al., Symptoms of outpatients as data for syndromic surveillance (summary), Journal of the Japanese Association for Infectious Diseases (Kansenshogaku Zasshi) 80: 366-376 (2006). http://journal.kansensho.or.jp/Disp?style=abst&vol=80&mag=0&number=4&start=366&lang=EN

[9] STFC, National Institute of Science and Technology Policy, Health regulations responding to international public health crisis come into effect. Science & Technology Trends 77 (2007). [in Japanese]

[10] Lori UP et al., A survey of usage protocols of syndromic surveillance systems by state public health departments in the United States. J Public Health Manag Pract 15: 432-438 (2009).

[11] Inter-ministerial Pandemic Influenza and Avian Influenza Committee, The Pandemic Influenza preparedness Action Plan of the Japanese Government (2009): http://www.cas.go.jp/jp/seisaku/ful/kettei/090217keikaku.pdf. [in Japanese]

[12] Infectious Disease Surveillance Center, National Institute of Infectious Diseases, Syndromic surveillance, Surveillance of prescription medication at dispensing pharmacies: http://www.syndromic-surveillance.net/yakkyoku/index.html. [in Japanese]

[13] Yasushi Ohkusa (research representative), Empirical Study on early detection of local health crisis management information and information sharing systems including government institutions. FY2009 Health Science and labour research grant from Ministry of Health, Labour and Welfare. Multidisciplinary research project report on health and safety crisis management measures (2010). [in Japanese]

[14] Polgreen PM et al., Using internet searches for influenza surveillance. Clin Infect Dis 47: 1443-1448 (2008).

[15] Ginsberg J et al., Detecting influenza epidemics using search engine query data. Nature 457: 1012-1014 (2009).

[16] Google.org. Google Flu Trend: http://www.google.org/flutrends/intl/en_us/jp/#JP.

[17] Wilson N et al., Interpreting "Google Flu Trends" data for pandemic H1N1 influenza: The New Zealand experience. Euro Surveill 14: pii=19386 (2009).

[18] Chretien JP et al., Syndromic surveillance: Adapting innovations to developing settings. Plos Med 5: e72 (2008).

[19] e-Stat, 2008 Survey of medical facilities (static and dynamic), Part 1, J109, No. of general clinics (multiple recording) by electronic medical record system, by bed availability and founder. [in Japanese]

[20] Strategic Headquarters for the Promotion of an Advanced Information and Telecommunications Network Society (IT Strategic Headquarters), New IT Reform Strategy (January 19, 2006): http://www.kantei.go.jp/jp/singi/it2. [in Japanese]

[21] May L et al., Beyond traditional surveillance: applying syndromic surveillance to settings – opportunities and challenges. BMC Public Health 9: 242 (2009).

[22] Jones KE et al., Global trends in emerging infectious diseases. Nature 451: 990-993 (2008).

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Trends in R&D in TSV Technology for 3D LSI Packaging

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1 Introduction

Small, high-speed, and multi-functional computers and other electronic devices have been enabled by high integration technologies that have come to reality by the miniaturization through the LSI process scaling which uses a very fine pattern. However, an upper limit in the progress of such miniaturization has come into sight. The miniaturization will be technologically limited due to the increase of leak current which generates heat in transistors, and signal delay time caused by wiring. 3D packaging technology is one of the technologies that are expected to make a breakthrough such miniaturization on a 2D surface, which will enable high density integration that does not depend on miniaturization on 2D surfaces. By stacking LSI chips, which would conventionally be set out on a plane, it will be possible to produce LSI components, with the same functionality as that of the components produced by conventional methods, and with a smaller footprint.

The 3D packaging key technologies are electrical packaging technology, which means that it is vital to connect the stacked chips electrically. Conventional 3D packaging technology uses wire bonding with fine metal lead wires. Recently, novel technologies have been developed to replace wire bonding. For example, wireless connection for data communication, which will reduce the space needed for wiring, has been proposed.[1-4] Another example is through-silicon via packaging technology[5-7] (hereinafter, referred to as TSV technology), which uses through-holes in silicon substrate for electrical connection. By using TSVs, it is possible to save the space that would be necessary for bonding wires and to make wiring lengths shorter. TSV technology is moving further ahead of other novel 3D packaging technologies mentioned above towards the production of commercially viable LSI components.[8,9]

In this article, TSV technology is introduced as one of the 3D packaging technologies. At the same time, as well as discussing the features of TSV technology, the technological challenges for attaining commercial viability are introduced. Finally, the R&D organizations or the consortiums both in Japan and in other countries, which have been working to tackle these challenges, will be introduced.

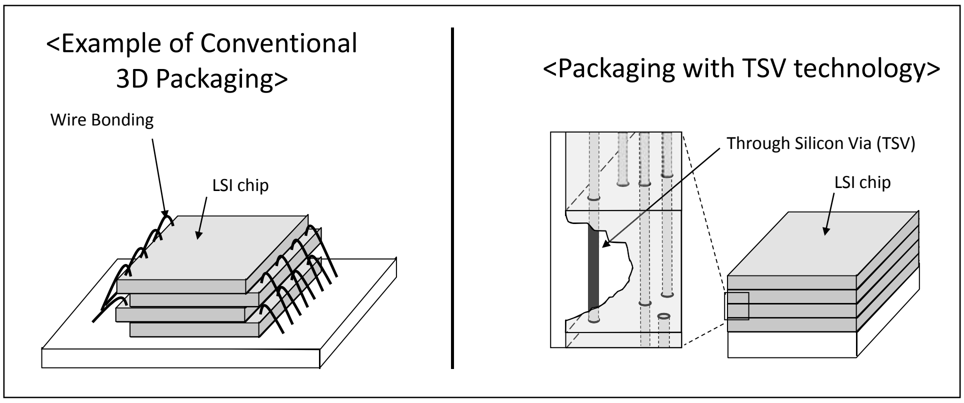

Figure 1 : Comparison of Conventional 3D Packaging and Packaging with TSV technology

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2 What is Through Silicon Via (TSV) Technology?

2-1 TSV technology for 3D LSI Packaging

3D LSI Packaging, which is expected to improve packaging density, has conventionally been accomplished by connecting chips electrically with wire bonding. TSV technology, one of the advanced 3D packaging technologies, is expected to improve packaging density compared with that using wire bonding.(Figure 2)

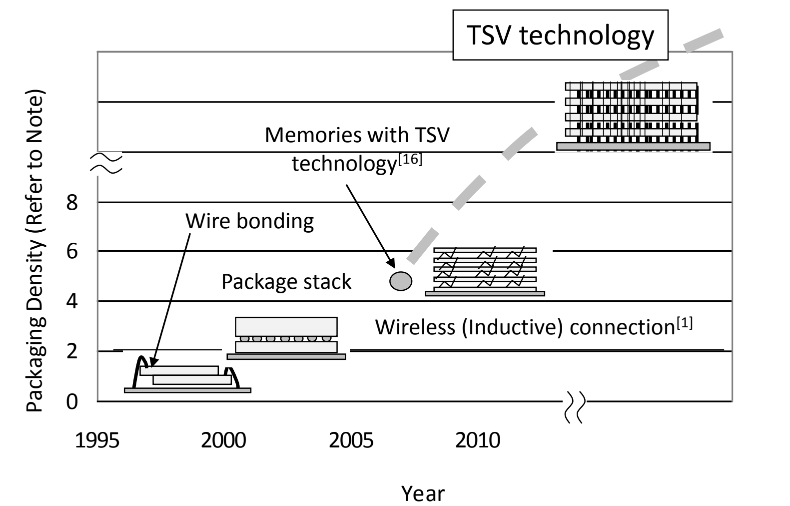
By using TSV technology, circuits in the stacked LSI chips are interconnected (Figure 1) by electrical connection through vias (TSVs) so that those chips can be integrated into an LSI component. TSV technology has attracted attention as alternative advanced technologies to replace the conventional process scaling of LSI. Furthermore, TSV technology is expected to be technologies to enable multi-functional LSIs, because of their capability to integrate heterogeneous LSI chips and/or MEMS in a single package.

Japan has led the world in the research and development in TSV technology for 3D high-density packaging since the Association of Super-Advanced Electronics Technologies (ASET) started the packaging technology research projects supported by MITI (now METI) in 1998 and kicked off its activities as the R&D center of TSV technology for high density packaging.[10] In the industrial sector, in 2007, Toshiba Corp. succeeded in reducing the volume of a mobile phone camera module by 64% by applying a TSV technology (Toshiba called it TCV, Through Silicon Chip, at that time) for the first time in the world,[8] and attracted attention from all over the world. Elpida Memory, Inc. announced that it had developed a DRAM of eight stacked LSI chips that had an eight times larger memory capacity than conventional ones.[9]

Although a lot of commercially available products using TSV technology have been announced, they were all merely examples of limited applications of the technology, where only miniaturization and high-density integration, from among various advantages of TSV technology, were achieved. On the contrary, current R&D activities worldwide are focused on the more advanced and more sophisticated applications of TSV technology which use the full range of the advantages of TSV technology, and an innovation in chip design methods also becomes a research target.

2-2 Two directions of TSV technology

The miniaturization and high-density integration methods of LSI are generally classified into two categories. The method in the first category is an implementation method called SiP (System in package) and the method in the second category is one of the LSI design methodologies called SoC (System



Note: Packaging Density is calculated by (the number of stacked LSI chips)/(the diameter of a interconnecting wire or via between LSI chips) and normalized by such value in the case where two stacked LSI chips are connected through a wire of 30μm diameter.

Figure 2 : Transition of 3D packaging

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on a chip). In SiP, individually manufactured LSI chips are integrated and combined into a package with ports for outer connections to form a single device. In SoC, a chip is designed in such a way that logic circuits which contain functional circuit blocks are realized in an single LSI chip. TSV technology has been developed to be applied in both categories that are said as both directions. Below, TSV technology is introduced in detail along the lines of the two directions referred to above, namely SiP and SoC:

(1) TSV technology as an extension of SiP

Basically, in SiP, LSI chips are interconnected electrically by metal wires. SiP technologies have been frequently applied to 3D packaging for digital cameras and mobile phones in order to miniaturize them by integrating chips with high-density. Fig 3 illustrates TSV technology as a next technology of SiP. As illustrated, heterogeneous LSI chips, adjacently placed or stacked, are interconnected electrically through an interposer (an interconnecting substrate for connecting between LSI chips) by wire bonding to be completed as an LSI component (upper-left of Fig 3). By contrast, in TSV technology, heterogeneous LSI chips are stacked and electrically interconnected through vias, not through wire bonding. The camera modules and the stacked memories referred to in 2.1 are examples of the expansion of SiP. Such extended methods of SiP are expected to be applied to the integration of various types of LSI chips on a chip (heterogeneous LSI) or to the packaging of LSI chips and/or MEMS together in a single package.

(2) TSV technology as a conceptual leap from SoC

Figure 4 illustrates how the SoC method originally used for a 2D design changes into for a 3D design method and how it can be applied to 3D packaging. It is a kind of conceptual leap. The conceptual leap occurs as follows: first, dividing a logic circuit composed on a 2D surface into multiple sub logic circuit chips; second, laying them out on multiple chips(silicon substrate); and finally, stacking the chips perpendicularly. TSV technology enables implementation of the same functionality on a smaller footprint. Therefore, as in the case of miniaturization or high-density integration, TSV technology is similarly effective in the scaling of LSI. Although commercially viable examples are not yet to be seen, high-density integrated logic LSIs will be considered to be one of the embodiments thereof.

2-3 Advantages of TSV

The advantages of applying TSV technology in comparison with conventional methods are as follows:

(1) Small size and high density

As illustrated in Figure 3 and Figure 4, TSV technology enables the miniaturizing of LSI components. Although SiP has been used for stacking, SiP requires excessive spaces outside the LSIs for wire bonding. In contrast, TSV is more effective for miniaturization because TSV requires no such spaces. As for a “conceptual leap from SoC,” TSV technology can be used for the perpendicular construction of LSIs in a 3D space, not on a 2D surface, and require a footprint at a fraction of that of a conventional LSI. On the other hand, as for high density integration, it has been reported that TSV technology can potentially be used effectively for stacking processor cores in a CPU composed of multi cores to realize a highly parallel processor LSI.

(2) High speed signal propagation and processing

As illustrated in Figure 3 and Figure 4, TSV technology can reduce the total wiring length, compared with 2D implementation. Shorter wiring lengths will lead to higher speeds in signal propagation and a reduction of mutual coupling which causes signal delays, and will finally result in high-speed data transmission. In addition, by using TSV technology, it is possible to increase the design flexibility, to reduce the wiring length and, finally, to increase the processing speed, by stacking and interconnecting LSI chips which transmit and receive data frequently. It has been reported that numerical simulations showed an increase of processing speeds up by 44% in comparison with the case of conventional LSI, by applying ideas such as those referred to above to increase the transmission speed between the processor and the memory in a supercomputer LSI.[11]

(3) Low power consumption

Electrical resistance causes heating. Further, since parasitic capacitance increases due to the length and the number of wires, charge/discharge current increases, then increasing current also causes heating. TSV technology, which can reduce the wiring length, enables the elimination of such heating and, as a result, reduces power consumption by cutting out power losses due to wiring resistance or parasitic capacitance. Furthermore, the shorter circuit length results in reducing the number of repeaters (signal reshaping components) while at the same time reducing the power required by such repeaters needed for compensating the decay and delay of signals. A simulation on the supercomputer LSI referred to in (2), showed that a power saving of up to 14% can be estimated.[11]

(4) Many input-output terminals

TSV technology also provides many input-output terminals. In a conventional SiP implementation, wire bondings are located at the edges of an LSI chip. Therefore, the input-output terminals have to be placed along the edges of an LSI chip. In contrast, in implementations using TSV technology, there is no such limitation on the placement of input-output terminals in an LSI. This capability of being able to place input-output terminals in arbitrary positions in an LSI chip without limitation leads to an increase in the number of interconnections (Figure 1), and also to an increase in the flexibility of circuit layout. Moreover, it is possible to explosively increase the number of parallel data transmission lines between

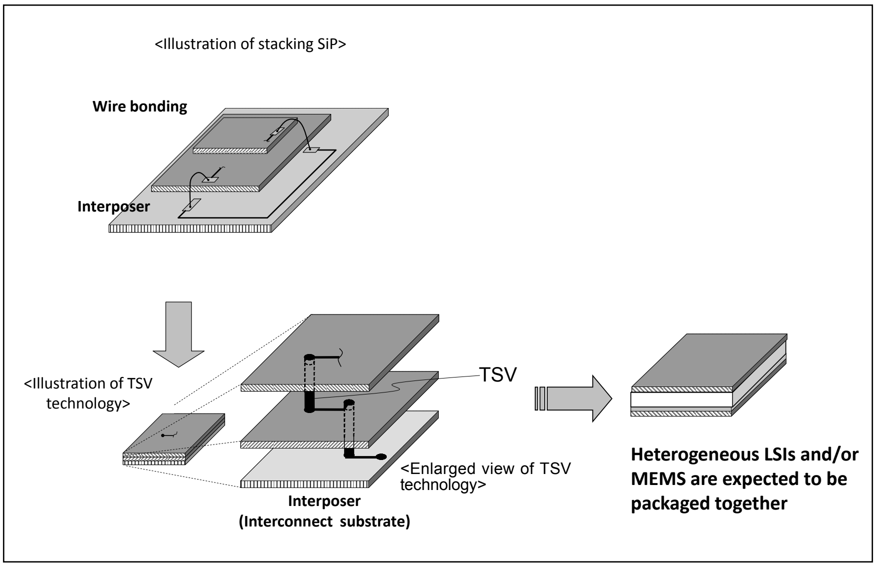

Figure 3 : TSV technology as an extension of SiP

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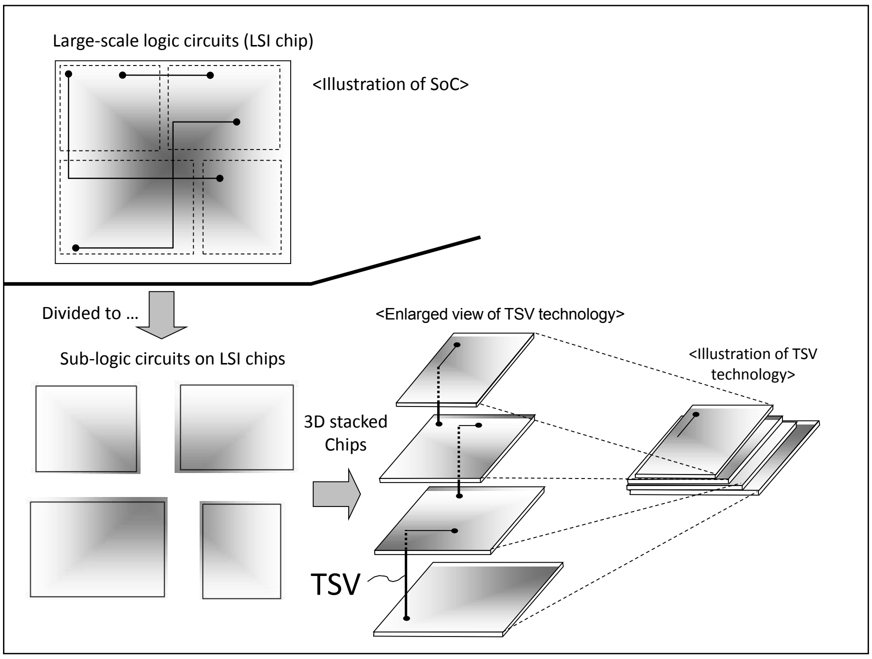

Figure 4 : TSV technology as a conceptual leap from SoC

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LSI chips and, as a result, to increase the data transmission speed, because of a number of input-output terminals.

(5) Multi-functionality and high performance

SiP technologies have been used to implement multi-functionality, and can enhance much more by using TSV technology enable to provide a number of input-output terminals. Then, more LSI chips can be implemented in a single package. For example, a high-resolution and high-speed image processor with the processing power of 10,000 frames per second can be constructed in a single package by integrating a large number of memory chips, a large number of high-speed processors and a large number of image sensors, working in parallel through a large number of input-output terminals produced by TSV technology.[12] This is an example of utilizing the advantages of integration and the high-speed capability of TSV technology. In such a way, TSV technology is expected to contribute to obtaining high-performance that would be difficult using conventional technologies.

2-4 TSV Application Targets

The requirements for TSVs differ from LSI to LSI, for instance, miniaturized LSIs require small-diameter TSVs and LSIs with large-scale circuits require a large number of TSVs.

Figure 5 shows various groups of LSIs, categorized by type or usage, in relation to the required TSV diameter and the required number of TSVs, where the horizontal axis represents the required diameter and the vertical axis represents the number.

As showed in Figure 5, the CMOS camera module, which has already been marketed, uses a small number of TSVs with a large diameter. The stacked-die memory, which has been announced, compared with the CMOS camera module referred to above, uses a larger number of TSVs with a smaller diameter. However the number of TSVs is still only around several thousands. Compared with those two earlier examples, Logic LSI components, expected to be developed in future, will require several tens of thousands of TSVs with a much smaller diameter. If the TSV's diameter is 1μm, up-to one million TSVs can be formed into a 1mm square. However, LSI components may use a variety of TSVs with different diameters on a single chip. For example, Logic LSIs will use small-diameter TSVs for signal transmission and, at the same time, for power supply, they will require large-diameter TSVs due to a large current capacity. Moreover, heterogeneous LSIs which contain different types of LSI chips integrated into one component, and MEMS consolidated LSI components will require a larger variety of TSVs with different diameters.

Therefore, the technical difficulty of forming TSVs differs largely from application to application, and thus it is not easy to discuss TSV technology in a uniform way.

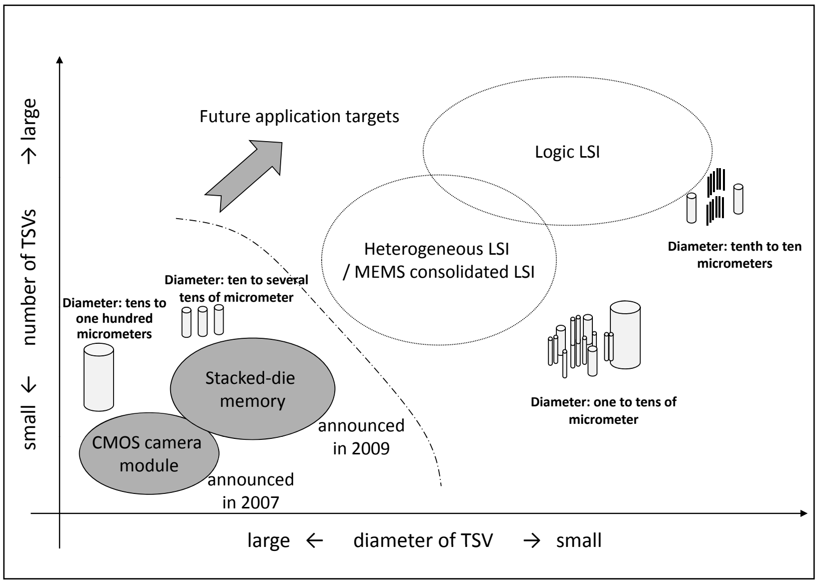

Figure 5 : Map of TSV applied components in relation with TSV diameter and number

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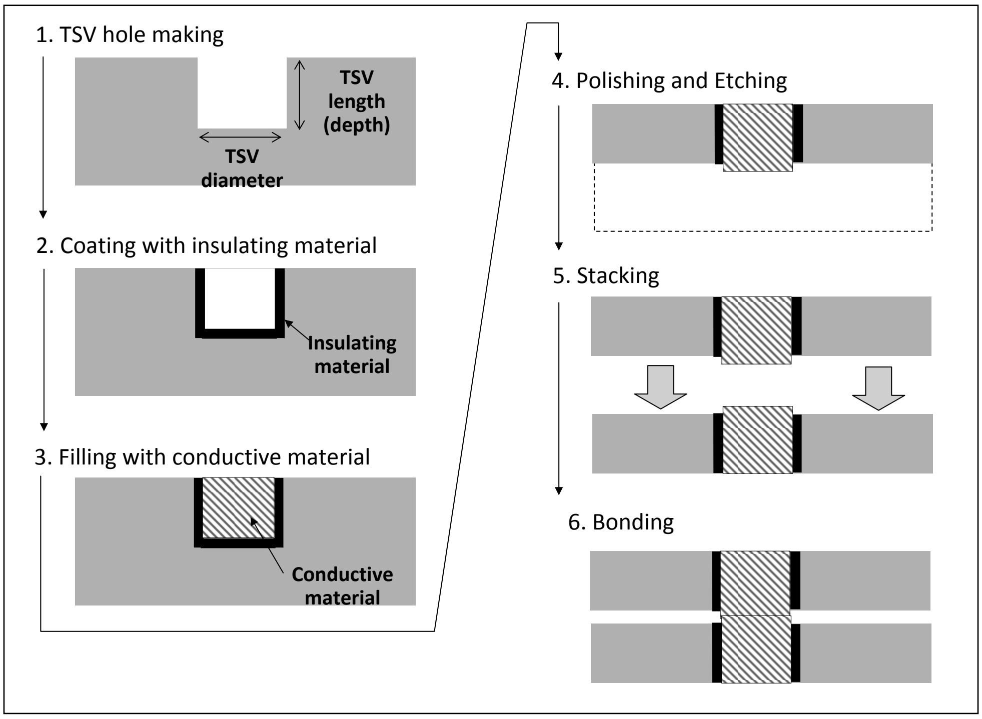

Figure 6 : TSV fabrication Process, illustrated in cross-section

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2-5 Fabrication Process of TSV

The TSV fabrication process consists of TSV forming process, chip stacking process and TSV bonding process.

First, a hole is made on a silicon substrate (Figure 6, 1). Then, the inside of the hole is coated with insulating material for preventing electrical conduction between the TSV and the substrate (Figure 6, 2). Next, the hole is filled with conductive material (Figure 6, 3) to become a via. Then, for the interconnection of TSVs, the bottom of the substrate, which is on the opposite side of the hole, is polished and etched to make it thinner in order to expose the TSV(Figure 6, 4). Finally, two LSI chips are stacked (Figure 6, 5) in such a way that the TSVs are bonded with each other, and a circuit connection through TSVs is established (Figure 6, 6).

3 Challenges in R&D in TSV

3-1 Primary Challenges in Fabrication

(1) TSV hole Forming

The first challenge in the fabrication process is to create a TSV hole on a silicon chip. TSVs require deep holes with a small diameter.

The aspect ratio of a TSV (TSV length / TSV diameter) reaches to several times to several ten times in the ratio. Making such a high aspect ratio hole is a significant technical challenge. Furthermore, as the aspect ratio rises, the difficulty in fabrication increases and the time taken for fabrication grows longer. How to choose the fabrication process, how to apply the process, and how to determine the diameter and length of the TSV are researched through experiment or trial and error.

As for "making holes," two processes are well known; the first is called the "Bosch Process,"[13] which is a "deep-etching process," originally developed for MEMS fabrication; and the other is called the "non-Bosch Process," which simply means that "it is not included in the category of the Bosch Process." The Bosch process, developed by Robert Bosch GmbH in Germany, begins with digging a shallow hole by Reactive Ion Etching(RIE). The hole is then coated with insulating material, and dug again. By repeating the process described above, a deep perpendicular hole is formed. RIE is a digging process where a specimen to be etched is placed in a chamber filled with reactive gas (etching gas), given electric potential, and exposed with ions or radicals to be hollowed.[14] On the other hand, in the non-Bosch process, a deep hole is formed by a sophisticatedly controlled anisotropic etching process and does not require the in-process insulation material coating which is required in the Bosch process.

The holes formed by the processes mentioned above are then coated with insulation material and filled with conductive material. The selection of the conductive material depends on the TSV forming process. How to choose the conductive material is left to section (4). The next section (2) will illustrate the polishing and etching processes.

(2) Polishing and etching

A silicon substrate is polished thinly to a thickness of several tens to several hundreds of micrometers in order to shorten the time required for TSV forming by shortening the length of TSV holes. This is done because TSV forming processes are very time consuming. Next, the substrate is etched thinly to expose a TSV. Also, the substrate polishing is an effective way to obtain a higher packaging density in a stacking direction and to produce thin LSI components. During polishing processes, silicon substrates suffer from mechanical stresses, therefore it is necessary to protect the substrate by supporting it with, for example, a glass carrier. Of course, the supporting glass carrier must be removed after completion of the polishing. A lot of effort has gone into research on how to choose the adhesive for bonding the glass carrier and how to remove it after polishing, as well as into other problems such as how to determine the process sequence or how to remove the dust brought about by polishing.

(3) Connecting

As for connecting TSVs, there are three methods called “Wafer to Wafer,” “Die to Wafer” and “Die to Die.” In “Wafer to Wafer,” silicon wafers are bonded to each other before LSI chip dicing, in “Die to Wafer,” chips diced-out of wafers are bonded to wafers, and in “Die to Die,” diced-out chips are bonded to each other. The process technologies for all three methods, which have both drawbacks and advantages as regards difficulties or costs, are targets for research. For example, in Wafer-to-Wafer, 300 mm wafer discs are bonded to each other in such a way that each of several thousands to several tens of thousands of TSVs with a 1μm diameter on a wafer disc is precisely interconnected to each TSV on the other wafer chip. It is easy to understand that a very high precision alignment is required. There are two methods for stacking TSVs: the “Face to Face” method and “Face to Back.” In “Face to Face,” circuits formed on an LSI are stacked face-to-face to the circuits on the other LSI. In “Face to Back,” LSIs are stacked in such a way that the faces are in the same direction. Different technologies are required for each method with different directions of stacking, and so, different aspects of research and development are necessary.

(4) TSV formation timing

TSV forming methods are categorized into three groups according to when in the process the TSVs are formed. These three methods are described in detail along with the generalized manufacturing process of LSI[15] illustrated in Figure 7. The first is called “vias first,” where TSVs are formed on a silicon substrate before circuits are built. The second is “vias middle” where TSVs are formed after circuit building and before wiring among circuits. In some cases vias middle is categorized as vias first. The final one is “vias last” where TSVs are formed after wiring. In some cases, TSVs are formed after stacking LSI chips. Such a case, although also called vias last, is positioned on the Assembly and Testing process in Figure 7.

These three processes, which have different timings for each TSV formation, require different TSV-filling conductive materials. In vias first or vias middle, polysilicon is used, because, in those processes, heat-resistance or process-compatibility is required. In vias last, requirements for materials are not so severe, and Cu (copper), W (tungsten), or Al (aluminum) is used.[16] The material for the filler needs to have high electrical conductivity, however polysilicon has high electrical resistance. On the other hand Cu or Al has low resistance. In addition, Ni (nickel) has been tried as a replacement for polysilicon which has not been used favorably.

As for the TSV formation, the best process timing has not yet been found and still is a research target.

3-2 Challenges in Significant Related Technologies with growing Difficulties

For applying TSV technology successfully, more complicated and sophisticated technologies are necessary than are required in conventional LSI manufacturing. Such technical challenges in the significant related technologies are described below:

(1) Testing

As for an LSI component composed by using TSV technology with several stacked LSI chips and/or

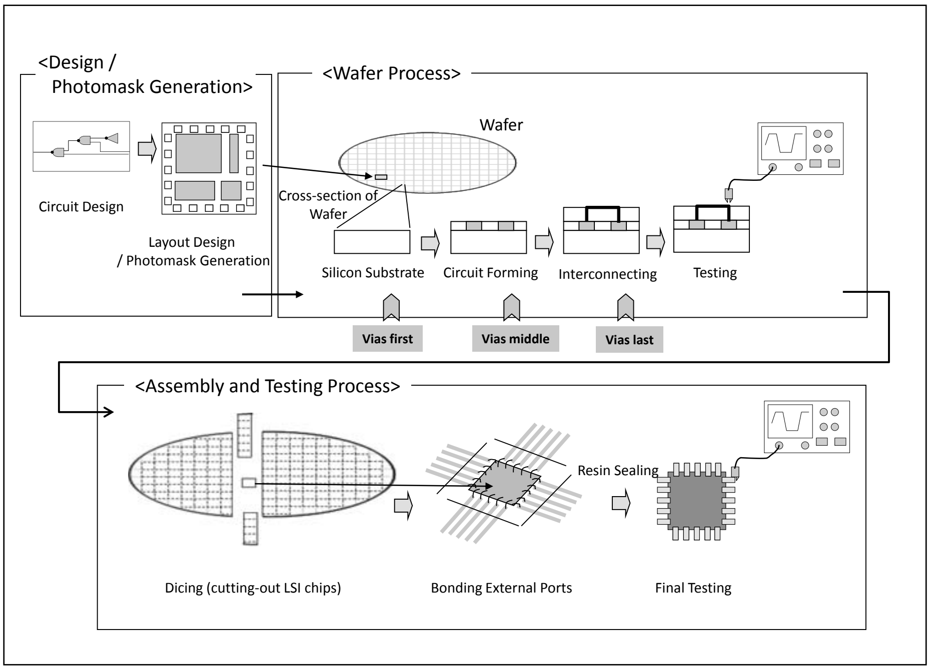

Figure 7 : Timing of TSV formation in the generalized manufacturing process of LSI

Prepared by the STFC based on Reference[15]

several stacked MEMSs, some test ports that would be necessary for the diagnostic test of LSI chips and MEMSs placed on inner layers may be hidden inside the component and not accessible from the outside. Such LSIs or MEMSs can be tested only through ports exposed outside the component. Therefore, more complicated test items and longer testing times are required because access from the outside is limited. To remove such inexpediencies, much more effort will have to be put into researching, for example, effective test programs with fewer test items and high-speed data gathering capabilities, or into analysis methods. If an LSI component fails a test, it means that a large number of LSI chips and MEMS are discarded, resulting in a great loss. Therefore, the verification tests of an LSI component become much more critical than for conventional LSIs.

(2) Heat design and heat dissipation

Generally, when LSIs are in operation they generate heat, and the generated heat raises the operating ambient temperature. When operated at a high temperature, LSIs lose their reliability. Therefore, heat design and heat dissipation are critical for ensuring reliability. For stacked chips, the heat design for chips on the inner layers is more difficult. In addition, when non-uniform heat is generated by an LSI chip, it causes mechanical stresses due to differences in heat expansion, leads to excessive force in TSV connection, and finally results in reliability degradation. To solve heat problems, ideas have been proposed such as forming dummy TSVs, with a view to making positive use of their heat conductivity for heat dispersion and heat dissipation.[17]

A more sophisticated heat design will be required for multiple stacking LSIs which generate much more heat. ASET, the research consortium referred to earlier, has reported experiments[5] where cooling water runs along the surface of LSI chips, as one of the water-cooling trials for high-end LSI components.IBM Corp. has reportedly started a research project for novel, their original, cooling technologies using a liquid coolant.

To solve heat problems, in addition to heat simulations in layout design or structural analysis which take care of mechanical distortions by heat, research and development efforts will have to be put into the codesign method which consolidates electrical design, heat design and structural design.[12]

(3) Analysis of Signal and Power Integrity

LSI components integrated by using TSV technology contain electrodes for perpendicular interconnections, which conventional LSIs do not have. The physical characteristics of various materials related to the interconnection electrodes, such as conductive material in TSVs, insulator material surrounding TSV and silicon substrate through which TSVs are made, have to be taken into consideration when electrical and electromagnetic characteristics are

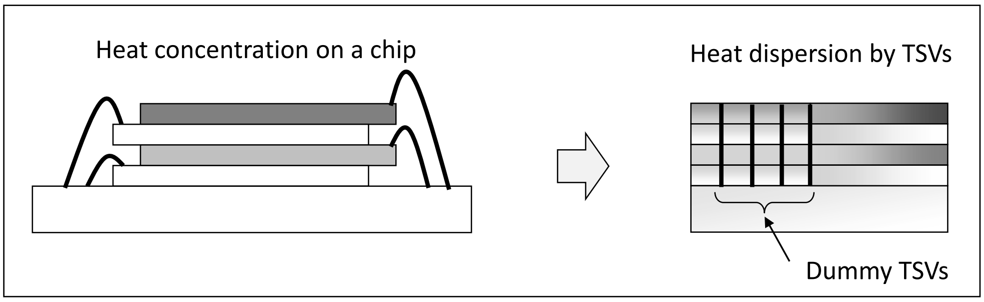

Figure 8 : Heat dispersion through TSVs

Prepared by the STFC

determined, because they are the critical factors that determine signal transmission quality. At the same time, research and development efforts are required on simulation models or model of computation of TSVs for analyzing SI (Signal Integrity). In order to build such simulation models, the ability to link circuit simulators with electromagnetic field simulators will be indispensable.

At the same time, it is important to make effective use of the know-how stored in conventional LSI design. For such practical use of conventional know-how, it will be necessary to apply the design methodology of a "what-if analysis," where the design process proceeds through a "parameter-change analysis" based on hypothesis and assumption. High-speed simulators will be indispensable for such what-if analysis.

On the other hand, high PI (Power Integrity) is necessary for the stable operation of LSIs. High PI means that a circuit has a low voltage drop in a DC component and also has a low voltage fluctuation in an AC component.

Voltage drop in a DC component is basically determined by the diameter of TSV and DC resistance to conductive material that fills the TSV. It means that the diameter and the DC resistance are the critical factors. Similarly, capacitance and inductance are the critical factors of AC fluctuation. Capacitors can be effectively used for suppressing high-frequency voltage fluctuation. To use capacitors effectively, it is necessary to place them as close to the LSI chip as possible. Even embedding capacitors in the chip or in the interposer may be necessary in some cases. Therefore, capacitor embedding technology may be required.

(4) EMC: Electromagnetic Compatibility

In some cases, electromagnetic interference affecting the stable LSI operation may occur due to electromagnetic coupling between unconnected circuits. In TSV applied LSIs, electromagnetic interference between circuits is not negligible because circuits are placed closely within a short distance of tens of micro meters to circuits on other LSI chips, or TSVs are placed close to each other by several micro meters, and at the same time electric signals of various voltages and frequencies congest on an LSI chip as a result of packaging multiple LSI chips and/or MEMS. Generally, it is effective, in order to suppress electromagnetic interference, to place the reference potential (ground) of a large area close to the circuits and to give it a stable potential. However, in a TSV applied LSI, it is difficult to place the common ground of all the circuits because the circuits are multiple stacked.

In addition, research and development for electromagnetic noise emission control is also important. In some cases, such electromagnetic interference may adversely affect the operation of other outside instruments and devices. Therefore, the upper-limit of an allowable emission of electromagnetic noise from electronic devices has been determined by international standards, and additionally in Japan such emissions are restricted.[18] Countermeasures for electromagnetic noise emission will be more complicated for LSI components of a larger scale and with more functions as a result of the adoption of TSV technology.

So, such simulation technologies as used for SI or PI design will be critical.

3-3 Challenges in TSV design

The LSI manufacturing process is roughly divided into three processes; design process, wafer process and assembly and testing process (Figure 7). The design process, or the first process, is also divided into system design, logic design, layout design and test design. In recent years, an option of the manufacturing process has also been regarded as a part of design process, because design and manufacturing are closely inter-related. The design technology is a technology to design marketable products with optimizing all the manufacturing processes under electrical or mechanical constraints or conditions. The design technology will be realized by using design support software tools such as EDA (Electronic Design Automation) tools based on design concept (architecture). Two essential points in the design process when TSV technology is applied are as follows;

(1) TSV specific Design Challenges

As referred to in 2-3, 3D packaging using TSV technology could expand design flexibility to a large extent. That is the performance of LSI components may, possibly, depend largely on the performance of the design. For example, the layout design of LSI chips or LSI components will be changed drastically by the adoption of TSV technology. Generally, in layout design, circuit components are placed and routed between them, and, as a result of the design, photomask data to be used in the LSI chip manufacturing process are generated. In the case of LSI components with large-scale circuits, TSV locations have to be determined in such a way that the total circuit length is minimized. To accomplish such layout design, a new design methodology and also a new EDA tool supporting the design process will have to be developed.

In addition, TSV technology enables direct circuit interconnections between LSI chips, and eliminates I/O interface circuit connection on a pad which is indispensable for implementation by SiP technologies to accomplish the connection. However, those interface circuits have the role of waveform shaping. So, in TSV design, there is a requirement for such waveform shaping to be taken into consideration. Furthermore, new dedicated design tools may be required to design efficiency for a better design.

(2) TSV Design Technologies for Competitiveness

Generally speaking, the core technologies of TSV technology are based on mastery of the manufacturing equipment for TSV formation. However, the best combination of those core technologies has yet to be found. So, in production of the LSI with TSV technology, each semiconductor maker chooses the appropriate technologies from among the core technologies and combines them to obtain the advantage by using own methods in order to maintain its competitive edge by utilizing its know-how on parameter setting and so on. For the development of the LSI with TSV technology, each semiconductor maker determines the overall component-design by taking into consideration all constraints such as manufacturability, market adoptability, product reliability and cost. Among the critical technical factors listed in the previous section, the most critical factor is "cost." Miniaturizing, high density integration and multi-functionality have already been achieved in SiP by using wire bonding. So, in LSI components designed by TSV technology, the most critical factor compared with that of SiP is cost. Device engineers estimate that the allowable rise in cost caused by the adoption of TSV technology will be about 200 US dollars per one 300 mm wafer. However, future target has been set at 50 US dollars in one view,[19] and a Japanese venture company has announced a key technology that is expected to attain that target.[20] To keep on absorbing such new technologies and customizing them to create their own products will lead to better strategies for maintaining competitiveness.

4 Worldwide Research Organization on TSV technology

Research and development is being undertaken all over the world to solve the challenges referred to in chapter 3. Table 1 lists major public research organizations worldwide which are working on research and development in TSV technology, such as semiconductor design and processes or nano-scale fabrication. In this chapter, research and development projects aiming at the production of market adoptable products are introduced, focusing on their distinctiveness or originality.

4-1 SEMATECH (Semiconductor Manufacturing Technology Institute), US

SEMATECH in the US launched the TSV development program "3D Interconnect" in March 2007. Since then, they have been inviting participants to cooperate in the program. They say that the cooperation will be fostered in the "area of basic, precompetitive R&D." This means that

Table 1 : Major Public Research Organizations worldwide

Organization	Location
SEMATECH (Semiconductor Manufacturing Technology Institute)	US
Georgia Institute of Technology	US
Massachusetts Institute of Technology	US
Rensselaer Polytechnic Institute	US
RTI International	Offices around the world (established in US)
University of Arkansas	US
MIT Lincoln Laboratory	US
IMEC (Interuniversity Microelectronics Center)	Belgium
CEA-Leti (Electronics and Information Technology Laboratory of the French Atomic Energy Commission)	France
Fraunhofer Institute for Reliability and Microintegration	Germany
IME (Institute of Microelectronics)	Singapore
ITRI (Industrial Technology Research Institute)	Taiwan
ASET (Association of Super-Advanced Electronics Technology)	Japan
Tohoku University	Japan

Prepared by the STFC based on the Reference[5]

participants will cooperate in an area where they are not competing with the others. The distinctive points regarding SEMATECH are described below:[21,22]

(1) Variety of Participants

Various companies from all over the world are participating, including semiconductor dealers, chip makers, materials suppliers, assembling and packaging companies, design laboratories, test laboratories and test equipment makers, from every sector of the semiconductor industry.

(2) Practical Approach

They are addressing the challenges in TSV technology development in a practical way such as:

{1} Building a consensus in the semiconductor industry on 3D packaging methods, manufacturing processes, supportive tools and so on,
{2} Accumlating practical knowledge, such as the cost of each manufacturing process or other product specific information,
{3} Developing a practical and applicable manufacturing method,
{4} Building a roadmap and making efforts toward standardization.

(3) Other Features

SEMATECH allows the participants to use its new manufacturing technologies. It works on incentives to invite participants. In addition to this program, SEMATECH has a close relationship with Tokyo Electron Ltd.,[23,24] which is an LSI manufacturing equipment maker, and they have worked together in the development of the etching equipment for TSV forming. Such close relationships and strong alliances with semiconductor manufacturing equipment makers have enhanced SEMATECH's technological development capability in the semiconductor manufacturing process, especially in as regards the "wafer process" in Figure 7. Furthermore, in the wafer process area, SEMATECH has been undertaking collaborative research with universities such as CNSE (College of Nanoscale Science and Engineering).

4-2 IMEC (Interuniversity Microelectronic Center), Belgium

In 2004, Belgium-based IMEC started research and development in basic TSV technology, and has boosted its activities since it launched a specific project for 3D packaging by using a cooperation scheme called IIAP (IMEC Industrial Affiliation Program) in 2006. This project aims to develop 3D packaging technologies, and also undertakes penetrating research into design problems. The characteristics of the project are as follows:[25,26]

(1) Variety of Participants

The project has alliance partners from all over the world, including IDMs (integrated device manufacturers: semiconductor maker which design, manufacture and sell, semiconductor products), packaging companies, fabless/fab-lite semiconductor makers, EDA tool providers, manufacturing equipment makers and materials suppliers.

(2) Innovative Approach

The project focuses on 3D interconnections of circuits between different layers, and covers almost all levels of interconnection, ranging from a LSI package to an LSI chip. At the same time, it seeks industry-relevant, cost-effective and innovative solutions. It currently aims at determining the application areas for critical design problems where system level 3D interrconnections are applicable, and also proposing the design methodologies for such interconnections. It has shown a roadmap of TSV technology, on which they have announced, as one of their goals, LSI circuit interconnections using TSVs with a precision of 0.1μm diameter. This project's activities in this area can be said to be an example of the "conceptual leap from SoC" referred to in 2-2.

(3) Other Features

IMEC has accepted EDA tool providers as cooperation partners. IMEC's approach differs from that of SEMATECH on that point. On the other hand, IMEC has been undertaking original and advanced research in addition to the project, and, as well as SEMATECH, has an accumulation of excellent world-class knowledge. Furthermore, IMEC has allowed its members to use the world-class advanced manufacturing equipment installed in IMEC, and it has been attracting participants.

4-3 EMC-3D (Semiconductor 3D Equipment and Materials Consortium), EU, US and Korea

EMC-3D, a cross-border project between the EU, US and Korea, was started in 2007 when CEA-Leti, France, announced its participation in the project. EMC-3D aims to undertake TSV technology development for 3D chip stacking and MEMS consolidation. The distinctive points of the project are described below:[27]

(1) Worldwide participants

EMC-3D is an international consortium of which members are materials suppliers and manufacturing equipment manufacturers from the EU, US and Korea. In addition, universities and R&D divisions of major semiconductor makers have participated as partners.

(2) Sharing R&D Approach

The members have their own R&D themes in their fields of expertise, and have R&D responsibilities on sub-divided themes in TSV technology such as TSV forming, wafer polishing, and LSI chip stacking and packaging. Their common shared objective is to develop practical and low-cost TSV technology to gain market adoption and to make trial production frequently.

(3) Other features

It is noteworthy that, as for semiconductor makers, it is the R&D divisions of such organizations that have participated in the work not their manufacturing division. Furthermore, government research organizations dedicated to basic research, such as the Fraunhofer Institute, Germany, and CEA-Leti, France, are also involved. Therefore, EMC-3D seems to have targeted the area of basic and precompetitive R&D, as well as SEMATECH. Reportedly, EMC-3D was established to compete with ASET, Japan. So, EMC-3D is a consortium in which major private corporations and organizations worldwide, except for Japan, have participated.

4-4 Association of Super-Advanced Electronics Technology, Japan

For the first time anywhere in the world, the ASET started R&D activities of TSV technology in 1999 as a consortium project. Now, another project is working on practical and market adoptive R&D projects. Those projects are managed under the unified theme of "3D-Integration Technology (Dream Chip Project)."

(1) Participants pursuing Practical Technologies

Electronic equipment makers, semiconductor makers, materials suppliers, manufacturing equipment makers and a packaging company from across the entire industry which is seeking practical technologies are participating. In addition, universities and the National Institute of Advanced Industrial Science and Technology[12] (AIST) have participated.

(2) Approach for Practical Application Oriented Research

Activities have been carried out as contract research of the New Energy and Industrial Technology Development Organization (NEDO) on themes relating to the industrial application of TSV technology, such as circuit simulation, electromagnetic simulation, SI and PI using interposers, testing, heat design, polishing and trial production of LSI components using TSV technology.[12,28]

(3) Other features

As for semiconductor manufacturing equipment makers, the companies that have expertise in testing are also participants in addition to the TSV forming equipment makers. This is one of the unique features of the ASET. The development of almost all the essential technologies in the TSV fabrication processes have been completed, and the major current research targets are concentrating on the significant related technologies referred to in 3-2.

5 Conclusions

TSV technology has attracted attention as high-density integration technologies replacing miniaturization through the LSI process scaling. At the same time, TSV technology is expected to be applied in the production of multi-functional LSIs through their capabilities in integrating multiple heterogeneous LSI chips and/or MEMSs.

R&D efforts in US are concentrated on essential technologies and the application of TSV technology; in EU, in addition to the essential technologies, new EDA tools are under development and the practical application of TSV technology is being pursued along the long-range landscape of technology application; EU, US and Korea associated research consortium, while continuing R&D in essential technologies, is focusing on trial production using TSV technology; and in Japan, under the ASET consortium, R&D efforts are being put into practical applications including significant related technologies. Each of these international research projects has its own concepts and is unique, and it seems that Japan is working most closely to the "production."

Although the application of TSV technology brings a lot of advantages such as high-speeds, low power consumption, multi-functionality or high performance in addition to miniaturizing and high density integration, there are still a lot of technical challenges to be tackled. A variety of technical challenges ranging from design and TSV forming to significant related technologies will need to be tackled. To overcome such challenges, much research is being carried out all over the world and across borders. The majority of this research is generally based on "global alliances", which should attract attention as a keyword in the development of cutting-edge LSI technology.

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References

[1] Kuroda Lab., Keio University, homepage: http://www.kuroda.elec.keio.ac.jp/publication/paper_and_lecture/2009.html

[2] Atsushi Iwata et al., "Problems and Prospect of 3D Integration using Wireless and Optical Interconnection Technologies" IEICE Technical Paper, Vol. 108, nNo.140 ICD2008 -53, pp89-94, July, 2008 (Japanese)

[3] Zenko Hirose et al., "Shared memory integrated device of three-dimensional Photo Coupling" Japanese Pat. Publ. No. 1986-003450

[4] Takaaki Yamada, "Laminated Chip" Japanese Pat. Publ. No. 2010-016238

[5] Manabu Bonkohara et al, "Trends and Opportunities of System-in-a-Package and Three-Dimensional Integration" Invited paper, IEICE TRANSACTIONS on Electronics, Vol.J87-C No.11(Japanese)

[6] J.U. Knickerbocker et al., "Development of next-generation system-on-package (SOP) technology based on silicon carriers with fine-pitch chip interconnection," IBM J. RES. & DEV. Vol.49 No.4-5 July/September 2005

[7] P. Ramm, "EUROPEAN ACTIVITIES IN 3D SYSTEM INTEGRATION-THE e-CUBES PROJECT," 12th Annual Pan Pacific Microelectronics Symposium, Maui, Hawaii, February 1, 2007

[8] Toshiba Corp. press release, October 1, 2007, http://www.toshiba.co.jp/about/press/2007_10/pr0101.htm

[9] Elpida Memory, Inc. press release, August 27, 2009 http://www.elpida.com/en/news/2009/08-27.html

[10] Sei-ichi Denda, "The State of Development of Through Silicon Via for Three Dimensional Silicon Chip Stacking," Journal of the Surface Finishing Society of Japan, Vol.58, No.12, 2007(Japanese)

[11] Kobayashi, "Greeting and Opening Remarks by Cyberscience Center," 11th Teraflop Workshop Oct. 19-20, 2009) (Japanese)

[12] Morihiro Kada, "*(Trends in 3D Integration Technologies and Expectations for Reducing Cost)*" Lecture in TSV Technology Conference Seminar 2009, April 16, 2009, held by Nikkei Micro-device Magazine (Japanese)

[13] http://en.wikipedia.org/wiki/Deep_reactive-ion_etching

[14] http://en.wikipedia.org/wiki/Reactive-ion_etching

[15] http://www.necel.com/fab/ja/line/line1.html (Japanese)

[16] Osamu Kato, "*(Development of Chip Stacking technology using Through Silicon Vias)*" *OKI Technical Review* 211, Vol.74 No.3, November, 2007 (Japanese)

[17] S. Arkalgud, "Challenges in 3D TSV Technology," SEMICON West 2009, July 15, 2009

[18] VCCI Council homepage: http://www.vcci.jp/vcci_e/general/objective.html

[19] *NIKKEI MICRODEVICES 2009 April*, No.286 pp18-21, April 1, 2009(Japanese)

[20] *NIKKEI MICRODEVICES 2009 December*, No.294 pp95-98, December 1, 2009(Japanese)

[21] SEMATECH homepage: http://www.sematech.org/research/3D/index.htm

[22] SEMATECH news release: http://www.sematech.org/corporate/news/releases/20070321.htm

[23] Tokyo Electron Ltd. Press release: http://www.tel.com/eng/news/2009/1203_001.htm

[24] SEMATECH press release: http://www.sematech.org/corporate/news/releases/20081029.htm

[25] IMEC homepage: http://www2.imec.be/content/user/File/Leafl ets/cmos-iiap-3D-2009_EN.pdf

[26] IMEC homepage: http://www.imec.be/ScientificReport/SR2008/HTML/1224952.html

[27] EMC-3D homepage: http://www.emc3D.org/index.html

[28] ASET homepage: http://www.aset.or.jp/english/e-kenkyu/research_items.html

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3

Promises of Cloud Computing: Underlying Technology That Supports Transformation "From Possession to Utilization"

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1 Introduction

The term "Cloud" represents a system of information processing based on the internet, which is often depicted metaphorically as a cloud floating over the sky. Computations and information processing are carried out, not by the computing machines at your fingers, but by computing resources cloud computing center located somewhere in the cloud, and the results are brought to your display.

Cloud computing is considered an evolution of the systems of computing power utilization from batch processing, remote processing, time-sharing processing, personal computing, and client-server systems. In a broader context, cloud computing is considered to embrace IT technologies and utilization activities overall in the near future, which will serve as the engine for transformations on people's personal lives, business activities and social frameworks, as these are promoted by the development of IT technologies and the prevalence of the internet.

Therefore, the term "cloud" allows a variety of interpretations depending on the viewpoint and on what aspect of it is in focus. There is a lot of debate about it, producing divergent opinions even among experts in this field.

In the report published by the Ministry of Internal Affairs and Communication "Report from the Panel on ICT Vision - the Strategy to Realize Smart Ubiquitous Network Society," June 5, 2009,[1] and the report from the "Study group on cloud computing and Japan's competitiveness"[2] which started from July 22, 2009, under the initiative of the Ministry of Economy, Trade and Industry, the terms "Cloud" and "Cloud Computing" are used in a broad sense that encompasses the whole of information-communication processing that will become increasingly dependent of the Internet. By the same token, this report uses the "cloud" in place of "cloud computing," and overviews the services it provides and its future potentials. This report largely skips the detailed descriptions of technological elements, as the readers can find many appropriate references elsewhere (see, for example, reference[3]) However, a short explanation of the environment surrounding the cloud (so-called "ecosystem") is given in this report.

All the potentials of cloud computing are not guaranteed to come to fruition in the future, and we cannot tell when they will become a reality. Mainframe computers, although being made a mockery of as surviving dinosaurs, are still in use. It is only natural to consider that a variety of computers and systems, including legacy systems, will continue to be used depending on the application.

We should rather see the innovative nature of cloud computing in such aspects as design scalability and the operational scheme of software that enables establishing cloud computing centers, an effort towards favorable TCO (Total Cost of Ownership) in a comprehensive manner with an eye to reduce CO_2 emission, and the underlying basic concept "from possession to utilization" and the realization of a scalable market on a global scale.

2 What is Cloud Computing

2-1 Services Provided by Cloud Computing

The services provided by cloud computing are broadly classified into the following three categories: (a) provision of hardware resources such as CPU, memory and storage, i.e. HaaS (Hardware as a

Services)/IaaS (Infrastructure as a Service), (b) provision of application software including word processors, spreadsheets, and customer management systems, i.e. SaaS (Software as a Service), and (c) provision of development environments for programmers, i.e. PaaS (Platform as a Service).

First, we will look into the overview of the HaaS (i.e. provision of hardware resources). To obtain this service, the user first accesses the website of the cloud service provider (the user is assumed to have already gained authentication), and input the required information for the cloud computer on the service screen: this includes configuration information of the computer (CPU specifications, memory capacity and HDD, the operating system to be used, etc.), period of use, and the utility rate. Upon receiving the request, the cloud center prepares a “virtual” computer in the data center according to the requirements from the user, and the user is allowed to use it through the Internet as if he/she has a real-life computer at his/her hand for the period he/she requested to use it.

The cloud hardware services currently available include Amazon Elastic Computer Cloud (EC2), Simple Storage Service (S3), Microsoft’s Azure, and others provided by internet service providers such as IIJ and Nifty. Amazon EC2, considered the herald of these lines of services, allows users to rent a part of Amazon’s internet-controlling computer resources and charges the user on an as-used basis. IBM’s Blue Cloud, on the other hand, aims at providing enterprise users with cloud services and it includes provision of dynamically scheduled computer resources for the development and testing of products in the IT and telecommunication areas. The underlying cloud center lines up tens of thousands of low-cost servers for the provision of cloud services at a low price.

Next, we explain the overview of the cloud software service, SaaS (Software as a Service). This service makes the applications (mail software, business software, etc.) deployed in the cloud center available to users through the Internet. Charging systems include as-used basis, license, as well as a free-of-charge scheme.

At present, major cloud software services include Google Apps (including Gmail, famous for its free-of-charge provision of up to 7GB capacity) and Salesforce CMR (the client management application provided by Salesforce.com).

The application software provided through the use of the Internet does not require installation on the individual PC; users are able to operate the software through a Web browser and memory and storage can be expanded as needs arise. For example, Google’s Gmail allows the use of email communications by simply setting up a mail account through the use of a personal authentication function provided by a cell-phone system. This service provides, despite the fact that it is free of charge, a range of high-level functions such as spellchecking, mail search and grouping, schedule alignment with group members, a sharable calendar, security protection (e.g. spam mail elimination), as well as allocation of disk space for mail storage. These functions are available to users without the need to install software on his/her own computer, and anyone who has an internet connection can access these services as a web service through the browser. This represents a typical SaaS application.

Next, we explain the overview of PaaS (Platform as a Service), referring to Figure 3. A software developer can develop his/her own application utilizing the development environment deployed in the cloud data center through the use of the Internet. The developed software will be made accessible to other users by starting the software on the cloud data center’s server. The developer may not even know the location of the physical server on which his development environment and data reside. These factors can lead to a substantial reduction in terms of time and cost for establishing and deploying a development environment.

As typical embodiments of cloud platform services at present, we can name the Google App Engine (provided by Google) and Force.com (provided by Salesforce.com). These provide the development and execution environment for user programs on the Web server. Microsoft has also started to offer the Windows Azure Platform: this platform is gaining attention among Windows software developers because it provides the conventional Windows development environment.

One of the most distinguishing characteristics to be pointed out about the cloud is its extensibility. Resources such as CPU, memory, and storage can be added and expanded as need arises, or automatically. The cloud also offers the flexibility to release redundant resources, delisting them from billing lists. The pay-as-you-go plan is the mainstream charging scheme employed for both hardware and software usage. This gives the user the advantage of very low

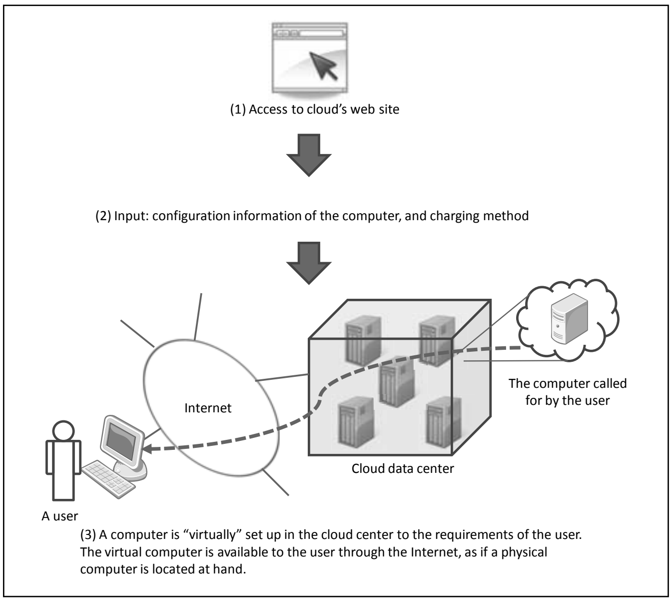

Figure 1 : Hardware Service Provided by the Cloud (HaaS)
Prepared by the STFC

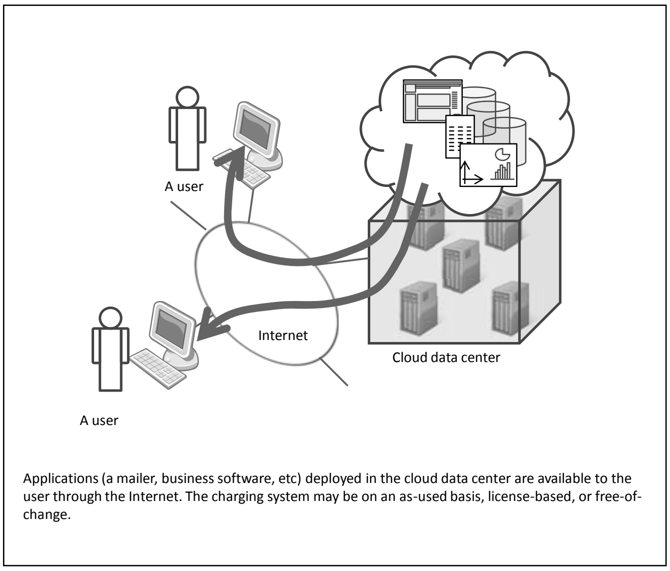

Figure 2 : Software Service Provided by the Cloud (SaaS)
Prepared by the STFC

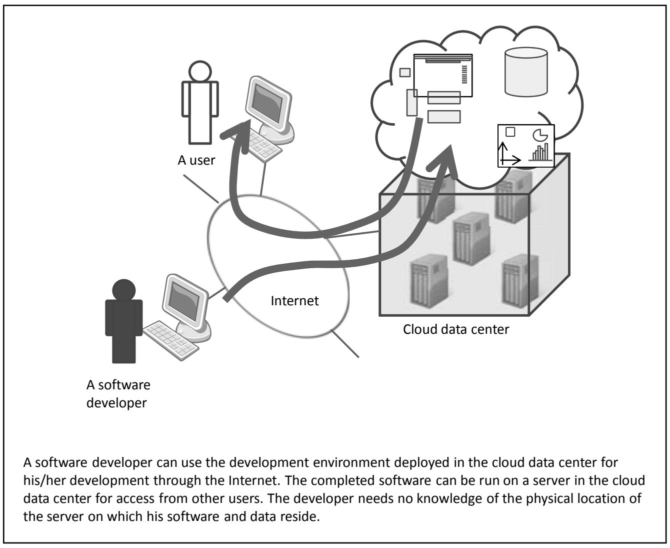

Figure 3 : Platform Service Provided by the Cloud (PaaS)
Prepared by the STFC

initial investment because he/she does not have to purchase the computer system. Cloud computing also releases users from troublesome and costly operations such as maintenance and version updates, because all of the operations are carried out in the cloud center.

2-2 The Environment Surrounding Cloud Computing and Underlying Technologies

2-2-1 Environmental Elements

The discussion of cloud computing technology (hereafter referred to as "Cloud") needs to be viewed alongside environmental factors, because a technology component, even if it is not novel per se, can bring out a new effect as the result of interactions with the environment.

The decisive driving factor, at least at present, that leads Japanese enterprises to introduce the Cloud, is cost reduction. However, a more important aspect to be noted is that the general paradigm shift "from possession to utilization" and the system change toward promotion of communication supports the basis of the Cloud, and development of the Cloud further strengthens these trends.[4]

The reasons for so much attention being paid to the Cloud is the view that it is poised to respond to current and future needs of society. First of all, there is a need in the business community, exposed to ever increasing uncertainty, that business organizations must transform themselves into more flexible and adaptable forms, enabling them to instantly cope with radical environmental changes. These requirements promote fluidization of resources at hand, including human resources, and a trend toward the service economy (i.e. simple delivery of goods is being replaced by the comprehensive provisions of services that include delivery of goods as a part of it). Information resources have to become more fluid to provide uninterrupted support for these trends. The Cloud offers an information platform to transform the nerve system of businesses (information system) into a more agile system that can conform promptly to the changes in the external world.

Secondly, there is a need to cope with globalization. The Cloud raises expectations because of its huge scalability that enables providing services to billions of users across the world. Thirdly, there is demand for environmental protection (e.g. the reduction of CO_2 emission) and energy consumption reduction.

Fourthly, there are demands to cope with a variety of new forms of information processing that came into existence accompanying the introduction of such subjects as e-Science, e-Government and smart meters.

2-2-2 Technology Infrastructure Elements

Technical infrastructure elements that support the Cloud include virtualization, the Internet, and ever-increasing sophistication and price reduction of electronic devices driven by Moore's Law.

The origin of virtualization technology dates back to the 1960s, when Virtual Machine (VM) technology was installed on the IBM360 series of computers. The virtual machines back in those days were developed for shared use of highly expensive mainframe computers. Today's virtualization has developed into technology that enables the offering of virtual systems, that run on a vast numbers of (i.e. tens of thousands of) mutually connected processors, to a great number of users.

Among the technology elements that support today's Cloud, system management that controls virtualization is the function most appealing to system users. In a cloud center that consists of a huge number of systems, it is customary that some of the systems are out of order at any time. Although some systems are under repair at any time, the center as a whole is managed to provide general users with sufficient and stable performance so that they rarely feel inconveniences (as affairs now stand, 99.9% availability is the operational target). Still, the cost required for system management is less expensive than that for dedicated systems that pursue extremely high availability.

It is apparent that the Internet and the underlying network technologies are essential to support the Cloud. Utilization of the network is an indispensable portion of Cloud usage. For enhanced security and convenience of the Cloud, efforts for further sophistication of the network and for optimum allocation of networks from a global point of view are essential now and will continue to be in the future.

As described below, higher functionality and lower price have to the proliferation of cloud centers. In view of the future of processor technology, the mainstream of development efforts aims at integrating more processor-cores on a single chip (many-core architecture). It is predicted that, sometime in the future, the system management technology currently applied to the assembly of a huge number of systems (i.e. the Cloud) will also be used to manage a computer with a many-core processor in it.[5,6]

2-2-3 Cloud Data Centre Technology

Among the Cloud related artefacts, the cloud data center (hereafter referred to as "cloud center") is the most easily comprehensible one. The cloud center, where a huge number - a few thousand to a few tens

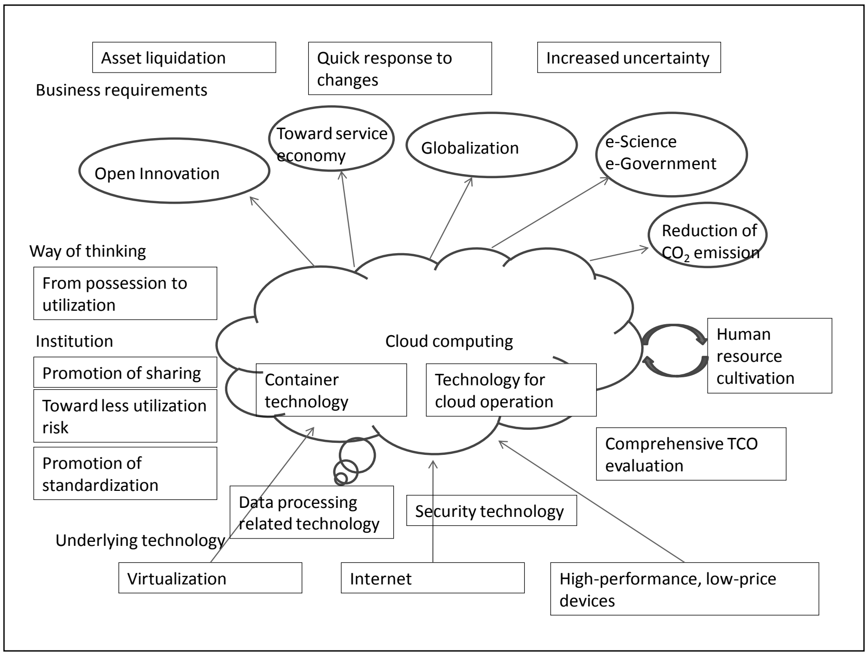

Figure 4 : Environment Surrounding Cloud Computing and Underlying Technologies

Prepared by the STFC

of thousands - of computing resources are centrally controlled, provides cloud functions to users across the world.

The cloud center is an extended form of a data center where all the computing resources are concentrated. However, it has evolved into something different not only in terms of scale expansion, but also in terms of policy and technology.

One of the basic policies is the reduction of TCO (Total Cost of Ownership) in a comprehensive framework. The "comprehensive" TOC differs from conventional TCO in its policy to try to reduce costs involved in all aspects of data center management - including power sources, air conditioning, labor costs, and CO_2 emission. In contrast, conventional TCO has focused basically on the costs involved in system hardware, software, and networks. The provision of computing power at a drastically reduced cost is one of the important factors supporting the growth of "change-free business"[7] innovation.

The container technology[8] – utilization of conventional containers packed with a number of computing systems - has recently gathered attention as one of the technologies applicable to efficient design of a cloud center. In this approach, the standardized container for international logistics is used as a unit to organize a cloud center. The modern containers have built-in features that allow naturally-cooled operation, enabling a substantial cost reduction in cloud center construction. Concentrated arrangement of these containers and proliferation on an as-needed basis provides a quick and cost-effective way to cope with the huge demand for information processing.

New operational strategies, that have no history in conventional data centers, have also been introduced. For example, as the hardware cost of data centers such as elemental equipments, processors, disks (including flash memory type) and routers, as well as power consumption, keeps going down according to Moore's Law, total replacement of these elements, say, in three years time, will become more favorable from the point of view of comprehensive TCO reduction. The fixing plan for failed system elements has also been changed: they are not replaced on an as-detected basis, but replaced collectively on a regular inspection round basis, as these failures have little adverse effect, even if they are left untreated, on the overall computing power efficiency. These operational approaches have a substantial effect on comprehensive TCO reduction.

2-2-4 Data Related Technologies

In terms of data and its management, data portability for the users and the related management schemes are gathering attention. The commercially operated Cloud, at present, does not guarantee the portability of user data, and from an institutional point of view, the policing and judicial system applied to the data depends on the region where it is thought to reside physically. This is not a reasonable judicial system for the users accessing the Cloud from different regions of the world.

Large-scale parallel processing technology, one of the major capacities of the Cloud, has been receiving attention. Although the core of this technology resides in virtualization and system management techniques, basic policies on database processing and transactions, or the aspects near the application-side, are also poised for radical changes. In database and transaction processing, integrity and consistency have been considered to be the properties of utmost importance. The newly developed technology in the framework of the Cloud, however, places the priority for the high-speed processing base on the scale-out capability of parallel processing rather than on integrity and consistency. In particular, a database is processed based on the key-value pair scheme, not on the conventional relational database model, to enable high-speed parallel processing of a vast amount of data. In transaction processing, a new technology called "eventual consistency"[9] have been implemented: this approach does not employ techniques that guarantee consistency at all times (e.g. two-phase commit) and confirms consistency once a parallel transaction of a vast amount of data has been completed. Furthermore, the generalized concept of such calculation technique ("failure-oblivious computing"[22]) has been propounded. This approach does not take corrective action against consistency errors on an as-detected basis, and continues processing only logging the occurrence of the error. The adoption of "eventual consistency" and "failure oblivious" applications for database/transaction processing means that business places priority on higher speed and scale-out of business transactions as a whole, even with some penalty of integrity and consistency. The new business models based on the Cloud may trace a different route from the extension of conventional businesses. These new breeds of business models include the Google search engine and Amazon's recommendation system.

The setup of "cost-free" businesses described earlier is considered in line with this trend.

2-2-5 Security Technology

Security is regarded as the weak underbelly of the Cloud: technology development is proactively pushed forward to overcome this problem. As one of the new schemes, "Virtual Private Cloud (VPC)"[23] has been introduced. The provision of a security-tight virtual environment is a possible option, and other options have also been proposed, one of which tries to turn the aspect of the Cloud generally considered as a weak point into an advantage (e.g. concealment of physical location of data), and avoid attacks and data leak by actively dispersing the data.[10]

Protection of general users against fraudulent practices and service providers against malicious attacks such as DOS (Denial of Service) is an important challenge: there is effort afoot to secure network security by eliminating malicious users at the network connection level.

Various methods are being deliberated to cope with this problem while paying due account to such factors as security, risk, and the reality of actual network operation. In line with this, upgrading the framework and standardization of network operation, including the modification of international law systems, are being discussed. This issue involves the scope of legal liability the Cloud undertaker should shoulder, and how to assure the safety of information. Concerns over information security from the viewpoint of the nation also seem imperative (see Chapter 6 "Cloud Centers in Japan").

On the other hand, with the ever-increasing prevalence of the Cloud, the general attitude toward security itself has been changing. The younger generation, often called "Digital Natives",[20] has a tendency to openly discuss things that older generations would consider private and that one should not present in open media, using such vehicles as Twitter and SNS. As private sessions on the network become an everyday affair, the challenge for the future is shifting more toward protection of the arena against malicious outsiders, rather than piece-by-piece security protection. In business communities also, the involvement of information exchange using Twitter and its relation to formal public relation activities are being discussed from the point of view of corporate jurisdiction. Interdependencies among these factors, including personal elements, have been under evaluation from the perspectives of cost and efficiency.

3 Possible Changes Cloud Computing Can Bring About

We consider the impact that cloud computing may have on the world in which we live from three perspectives: society, business, and personal life. As already pointed out in the report "PC Grid Computing," 2005,[17] CPU power is considered to be over-deployed, i.e. the total of CPU power deployed in the world has already exceeded the level actually required by businesses and services. Still, proliferation of cloud centers, for the promotion of cloud computing, do not show any sign of ceasing. In the background of this trend, there seem to be changes in the underlying environment including: (a) the growth of new application areas such as YouTube (posting and sharing of movies) and iPads (electronic browsing of printed media), which were previously positioned out of the computing community, (b) mushrooming of new business models, such as "change-free" businesses, that presupposes an affluent supply of cheap computing resources.

3-1 Prospects in Social Changes

The Cloud represents a variety of possibilities for alleviating computation (information processing) related burdens in many aspects of our society. The reduction of burdens can be achieved by centralized management and sharing of dispersed computing resources, and through standardization of ICT services. For example, in view of the latest trend of global environmental protection and reduction of CO_2 emission, the shift to cloud computing can help reduce CO_2 emission from information processing related activities. Consolidation of computing power, hitherto scattered in diverse locations, in a cloud center has a straightforward effect of reducing electric power and water usage as a whole,[11] and it also has an indirect consequence of helping people work at home utilizing cloud computing. The reduction of social burden includes work reduction for constructing computing environments and for providing ICT-based services, and shortening of hours for installation. Looking at the same effect from another viewpoint, the consolidation effort also means that the huge workforce engaged in the development and service provision in the information processing sector will become redundant.[12]

Reduction of ICT cost with inexpensive ICT facility means reducing the burden of ICT system construction in terms of development labor and time. The reduction of ICT cost may have wider repercussions such as the replacement of existing services with cheaper ones using ICT, and the invention and introduction of new services that will fully take advantage of ICT will be facilitated. The trend will provide a possibility to accelerate the evolution of social systems and enhance the benefits of our society as a whole. On the other hand, heavier dependence of social activities on ICT may create such problems as widening disparity between ICT knowledgeable and ICT illiterates, and increased risk of ICT security.

3-2 Prospects in Business Changes

In the business community, the beneficial effect described above can be enjoyed by each group of enterprises including: reduction of burden, reduction of ICT cost and shortening of development period, and reduction of development burdens of new products and services in terms of cost and time. Utilization of the cloud renders it possible to make contact to all of the four billion Internet users (cloud users), giving a chance to even a small-sized company to directly access the huge market. The promotion of sharing resources, a typical characteristic of the cloud, will facilitate the proliferation of open innovations. This also facilitates the strengthening of inter-enterprise links: incorporation of a service provided by a company whose activities lie in a different area, and vice versa.

In Japan, installation of thin clients (a terminal used for connecting the in-house cloud with the outside world and inside the company) is under way as a measure against security hazards such as information leak. Some of the major companies have already removed mass storage (e.g. hard disks) from desktop PCs, and place all of the application software (word processing, mailing, etc.) on the cloud. The cloud terminals such as smart phones are considered to be used more widely within companies.

On the other hand, the widening of the accessible market will create increasingly fierce competition on a global scale, and there will be increasingly many cases where an unexpected competitor comes in out of the blue. Realignment of coalitions with other companies will become necessary more often, and this may lead to an increased number of critics and claims from customers. This may also lead to an oligopoly of services, increasing the uncertainty surrounding business operations.

3-3 Prospects in Personal Changes

A personal user cannot normally distinguish whether he/she is using cloud computing or simply using other Internet services, except when he/she is using PaaS or IaaS directly on a personal basis. For example, Gmail, one of the typical existing applications, may not be distinguished from the conventional free-of-charge Internet mail services, except for the capacity allocated and the number of related services. The following descriptions, therefore, overlap with many of the aspects surrounding an individual when “ubiquitous telecommunication” is realized.

Terminals, called a cloud devices,[13] will be available all over the world and play a major role in telecommunications. Cloud devices can be thought of as an enhanced form of ICT terminal such as the Notebook PC and Smartphone as we see today. Two types of cloud devices are expected to become prevalent: a mobile type which an individual carries with him/her, and a desktop/wall type installed in homes, offices, and public places. Both are equipped with multiple input/output functions such as voice, gestures and keyboard.

Personal information required for carrying out social life is stored and managed on the cloud. The cloud provides, through cloud devices, various procedures on a 24/7 basis and does not require special skill. On the other hand, cyber-crimes are expected to grow steadily, with criminals trying to get hold of valuable information on the cloud. Each individual will have to check the integrity of his/her information on a regular basis.

The prevalence of the cloud will give more entrepreneurial chances to an individual, as well as more chances for employment and more learning opportunities. On the negative side, however, the frequency of losing jobs is expected to rise, because enterprises/organizations will have to modify their organizations more often.

4 From Possession to Utilization

The truly revolutionary character of the cloud lies in the fact that it triggers a paradigm shift in information processing engines, i.e. "from possession to utilization." The people of older generations, say people over sixty, may feel as if this age harkens back to more than thirty years, from the point of view of computer utilization, when the sharing of mainframe computer centers was the mainstream. In those days, as computers were very expensive, shared use of a computer was the common practice, and proprietary possession of it by an individual or a company was exceptional. Subsequently, the dramatic increase of the performance-cost ratio of computing devices and drastic reduction of prices (Moore's Law) enabled possession of computers on an individual or a company basis. Although this is a rare and exceptional case, Microsoft distributed a laptop computer free-of-charge to each of the thousands of participants to the convention hosted by Microsoft (San Francisco, December 2009).[14]

The important factors that change the form of computer utilization – from proprietary possession to share use, i.e. the cloud – include the change of the underlying sense of values as well as the pursuit of cost reduction, enhanced convenience, and a wealth of applications. As exemplified by the prevalence of the Internet, information processing has become a day-to-day practice in all aspects of personal life, and we all now consider such an environment as a matter of course. The use of information technology is not any more limited to businesses and governmental organizations. The cost associated with the use of a computer has dramatically come down, owing to the prevalence, performance enhancement and much higher reliability of telecommunications infrastructure (typically, the Internet and cell-phones). The entry of ICT into almost all aspects of our lives, as well as the progress of standardization, made the use of ICT much less troublesome than before. Wireless networks, underlying the Internet and cell-phones, have become increasingly ubiquitous and faster, raising the level of convenience of usage to an unprecedentedly high level. Applications such as SNS and GPS, quite unthinkable in the conventional computing environment, have come into practical use, and they can be used freely from mobile terminals. Looking at the sheer number of people connected to the network, the billions of cell-phone users across the world are coming into view of these applications; a huge market is in the process of being made.

The concept of "sharing" as pushed forward by the cloud does not mean the reversion to "shared use of a computer center," which was necessitated by the inability to own a computer. It rather means to save the time and effort associated with personally owning a computer. Or, the utilization style can be expressed as "virtual possession." The situation is similar to the car sharing system: car sharing has been introduced not because cars are expensive, but to save the trouble associated with car ownership, as well as to be friendlier to the environment.

In cloud computing, the user can select an application freely from among the huge array of computing resources to fit his needs, and perform input and output from anywhere at any time using a cloud device at his/her fingers. This environment may give the user an illusion as if a colossal computer is behind the cloud device held in his/her hand.

In addition, the shift of the way of thinking – from proprietary ownership to shared utilization – will pave the way to a new realm of simultaneous sharing of applications and knowledge with others, and the development of open innovation to new directions hitherto unthinkable.

5 Areas Where Broad Innovative Changes Are Forthcoming

5-1 Innovation in Research and Development

Research and development of the Cloud has been largely driven by the pressing needs of business strategy, rather than the traditional buildup approach starting from the R&D of generic technology.

Google and Amazon first decided what types of services they would provide to customers based on their business strategies, and then designed the business processes and the infrastructures including IT, the enabler of the business process, in view of obtaining the optimum method to deliver these services. In the construction of IT infrastructure, they did not develop new computers to their purposes, but constructed a large assembly of conventional computers, taking into account the balance of cost and efficiency. Thus, giving priority to business, they started service delivery utilizing conventional technologies. Once the service was started, however, basic research challenges came into view to process a huge number of transactions. These research challenges included such items as data consistency[15] and development of a distributed file system (Amazon S3). The former challenge gave birth to a new transaction technology,[15] or BASE (Basically Availability, Soft State, and Eventual Consistency), which is an extension of the conventional data consistency concept of "eventual consistency." This represents a typical example of a business strategy driven (or solution-driven) approach, in contrast to the build-up approach where step-wise developments starting from basic research finally lead to commercialization of a product. To provide excellent IT services, while avoiding wasteful investment, a good methodology is required to lead the solution-driven research and development to a good result. Successful execution of the solution-driven development is the key for the development of Internet technologies.

5-2 Innovation in Business Process and Business Infrastructure

The prevalence of the Cloud and its underlying concept, "from possession to utilization," will trigger a major break in business processes and business infrastructures. Many of the businesses today handle information explicitly as a capital part of their business. The transition of infrastructure morphology, from proprietary to sharing, will surely affect many aspects of a business process.

Usage of a shared Cloud can take various patterns: an in-house Cloud that integrates the servers deployed within an enterprise on a section-by-section basis, a group Cloud that consolidates group businesses, and a commercial Cloud that serves unknown and anonymous users. The extent of innovation that will take place may vary depending on the environment and circumstances, but innovation is considered to progress both in static aspects (represented in terms of openness, visualization, and standardization) and dynamic aspects (represented in terms of swiftness, elasticity, and quick response to changes).

The business environment has been such that a business tries to gain an upper hand over others by taking sole possession of the business process and limiting information to its own use. The static aspects (openness, visualization, standardization) above represent the business attitude to open up the proprietary process, or replace it with a standardized one, to achieve a visualized and shared process for construction of a win-win relation among all those involved. Activities of APEC to visualize international logistics, and the move toward adoption of the International Financial Reporting Standards are considered in line with this trend.

The dynamic aspects – swiftness, elasticity, and quick response to changes – represent the concerns of business entities for elastic operation of business processes and business infrastructure, coping with the uncertainty they are facing. The flexibility obtainable from adopting the Cloud makes even an originally seasonal business become available throughout the year. Webpo, an online delivery service of New Year greeting cards, is an example of new breeds of businesses along this line. Many of the "cost-free" businesses have become a reality by converting fixed costs and expenses into variable expenses, where the flexibility of the infrastructure plays an essential part.

The Cloud not only helps innovating the above-described static aspects by realizing data and process sharing, but also the dynamic aspects by flexible provision of information processing resources.

5-3 Structural Innovation in Information Industry

The Cloud has the potential for triggering all-industry-wide innovative changes, leading to industrial restructuring. As described in 3-2, the Cloud helps in streamlining each of the industrial sectors by jettisoning redundant properties, as well as promoting active inter-business coalitions. As a result, rather than a scale expansion in the conventional ways of thinking, the ability to specialize in one's core business and to link with other businesses in an alert and agile way will be highly regarded.

In particular, the Cloud has the potential to bring about the following changes to the ICT industry, which is in direct contact with information processing.[12]

- Sales of computers to general users will be rendered obsolete by the introduction of cheap Cloud devices that provide the functionalities of wide range or computers including PC and cell-phone.
- Standardization of ICT related products and business moves further forward.
- Customization of information processing services such as system development/integration tailored to

the needs of the user will be rendered obsolete, and instead, the users will select one from multitude of applications, or combine them to suit their needs by themselves.

- As a result of these changes, workers involved in the conventional computer industry and information processing services will face the need to drastically change their business contents.
- Such activities as sales, lease, and outsourcing of a hardware/software service belong to a business model that carries meaning only in a market predicated on possession of goods (including possession only through a fixed period of time). Therefore, as the wheels of commerce change from possession to utilization, the business models of ICT enterprises will shift to the on-demand provision of component "functions" on the always-on network environment, and theses components will be selected or refused by the users.

6 Cloud Centers in Japan

Japan provides an ideal environment for cloud computing: it has well-developed Internet and cell-phone networks, whose prevalence, availability and reliability are counted as one of the highest in the world.

However, at present, there is no world-class cloud center in Japan. As described above, technology development for container type cloud centers has been well under progress overseas. In contrast to this, Japan is in a stage that a company (i.e. IIJ) has just begun a demonstration experiment.

As described in 2-2, the prices of the element components used for the construction of a cloud center have kept falling, and price-busting has become a day-to-day occurrence. The levels of service prices are also expected to fall in years to come, producing a fear to press on the management of small-sized ICT data center businesses as the investment recovery from existing facilities will become increasingly difficult. The advanced, large-scale cloud center businesses, on the other hand, may be able to enjoy this situation: they can keep a competitive advantage by lowering service prices supported by the benefits of comprehensive TCO reduction. New entry to this cloud center business sector may become increasingly difficult in the future.

Many factors are cited to explain why a world-class cloud center has not been constructed in Japan including the limited availability of land, geopolitical location (i.e. Japan is located in the far-east part of Asia), high risk from natural hazards (e.g. an earthquake), high cost (land, electricity, water, and labor), deficiency of human resources, and the lack of a preferential taxation system. Additionally, the inflexible and rigid law system has been pointed out. In view of the moves afoot to set up a cloud center in such areas as Singapore and Hong Kong, narrowness of land and high cost seem to lack persuasiveness. Rather, the institution of law may be a greater impediment. For example, the container-type cloud center constructed in the USA, as is, cannot be installed in Japan, where discrepancies with Japanese laws (Building Standard Act, Fire Service Act, etc.) are said to pose major barriers. This reminds us of the situation where, in the 1990s, Japan lagged behind in the development of search engines hindered by the lack of operational transparency of Japanese copyright law, resulting in the delayed start of search services business.

Given the perspective that many sectors of industries and services will depend on the cloud infrastructure, and if the situation in Japan continues as it is, Japanese users will have to rely on the cloud infrastructures and services provided by overseas enterprises and will have to keep paying the charges accordingly. Self-sufficiency and safety assurance in terms of energy and food has been a subject of continued debate. Discussion also seems necessary on how to maintain self-sufficiency and safety assurance in terms of information and its management.

7 Trends of Foreign Countries

In the United States, the most advanced nation in cloud computing, the government, under the leadership of GSA (General Services Administration) and other organizations, is actively promoting the use of cloud – IaaS, PaaS, and other services. For example, GSA's website has already begun providing computers and storage through the Cloud.[18] In Europe, as the EU directives forbid government organizations from using data centers located outside the EU area, data centers have been constructed in Ireland and other European countries. A cloud computing trade organization, EuroCloud, was established in October 2009. In Asia, cloud centers have been constructed, or are planned to be constructed in the near future, in China, Singapore, Vietnam, India, and Dubai. In Taiwan, the Taiwan Cloud Computing Consortium was established in April 2010, under the initiative of the Taiwan government.[19]

8 Human Resource Development for Cloud Computing

As is the case with all other technologies, development of human resources to support and utilize the Cloud is of utmost importance. In the United States, an industry-government-academia program (the Academic Cluster Computing Initiative[16]) is under way, and universities outside the United States, including Kyushu University from Japan, have joined the program. As well as the cultivation of human resources for technical aspects of the cloud, Japan urgently needs human resources capable of bringing about social and economical reforms utilizing cloud technology.

One method in this direction might be the establishment of an international internship program in collaboration with leading international companies in this business such as Google and Amazon. Firsthand experience on how an innovative idea, notion, or strategy is born and develops is an important factor that enables cultivation of a substantial number of “thought leaders” in Japanese society. This is not an issue for which we can rely only on the efforts of each company in the private sector; our society as a whole should tackle this issue.

Japan as well seems to be lagging behind in the development of human resources that support and utilize the cloud. Japan is also behind the other advanced countries in terms of the fostering of an ICT service industry, partly affected by the continued sluggishness of this sector that started already before the beginning of the cloud age. Thus, lifting up this industrial sector to a level capable of competing in the world is another challenge for Japan.

Turning our eye to the activities inside Japan, the Ministry of Internal Affairs and Communications (MIC) and the Ministry of Economy, Trade and Industry (METI) has set up a study group regarding cloud computing, and other plans such as the Kasumigaseki Cloud are under way. The Ministry of Education, Culture, Sports, Science and Technology (MEXT) is also sponsoring human resource cultivation projects for the cloud, but these measures seem far from sufficient.

9 Conclusion

This report overviewed the change in the way of thinking – i.e. from possession to utilization – toward the expanded scalability to enable embracing four billion Internet users across the world, whereby the authors called for the needs of Cloud utilization and improvement of the development environment.

The most immediate motivation for Japanese enterprises to introduce the Cloud, at least at present, seems to be the cost reduction. However, it should be understood to be a vehicle to trigger the transition from an possession-based to utilization-based economy.[24] The cloud, and the cloud center that supports it, represents a platform to realize such changes. In other words, the development of future cloud center technology serves as the central machine of the future industry. This technology development bears so much importance that it deserves all possible measures toward effective and flexible application of the legal system (e.g. establishment of a special economic zone).

Grid computing,[21] much discussed up until several years ago, has a common aspect with the cloud center in that both use huge computing resources, but the former provides services to only a limited range of the users, having made the discussion of its social implications slip away from attention. Accompanied by the rapid repletion of communication infrastructure in these several years, the cloud can now have a huge impact on society, especially on industries in general, so that the information industry sees its evolution both with huge expectations and full of concerns. It is not going too far to say that the fate of an enterprise in the information industry depends on how well it takes advantage of this opportunity. The cloud computing involves drastic changes in the business models used in a variety of sectors, which seems to trigger a tipping point to Japan’s information and telecommunication industry.

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References

[1] Ministry of Internal Affairs and Communication, Report from the Panel on ICT Vision, Jun 2009: http://www.soumu.go.jp/menu_news/s-news/02tsushin01_000017.html

[2] Ministry of Economy, Trade and Industry, "Study group on cloud computing and Japan's competitiveness," July 2009: http://www.meti.go.jp/committee/materials2/data/g90722aj.html

[3] Nikkei-BP, "The Complete Cloud Computing, from services to fundamental technology," 2009, ISBN: 4822283887

[4] Ministry of Internal Affairs and Communication, the document distributed at the 5th meeting of the smart cloud research group: http://www.soumu.go.jp/main_content/000054401.pdfl

[5] eXtreme Computing Group: http://research.microsoft.com/en-us/labs/ccf/default.aspx

[6] Futuristic Intel Chip Could Reshape How Computers are Built, Consumers Interact with Their PCs and Personal Devices: http://www.intel.com/pressroom/archive/releases/2009/20091202comp_sm.htm#story

[7] C. Anderson, "New strategy to gain profit from "free of charge"," Japan Broadcasting Corporation, 2009, ISBN: 4140814048

[8] ITMedia [2009/11/20] : http://blogs.itmedia.co.jp/business20/2009/11/post-bbdf.html

[9] W. VOGELS, Eventually Consistent, Queue vol.6, no.6(ACM), 2008

[10] ZDNet [2010/1/28] : http://japan.zdnet.com/sp/feature/10realtime/story/0,3800102676,20407595-3,00.htm

[11] "Introduction of the Cloud reduces approximately 60% of CO_2 emission," Mainichi communication journal, November 16, 2009 http://journal.mycom.co.jp/articles/2009/11/06/nec/index.html

[12] "Does the Cloud create a super competitive environment?": http://itpro.nikkeibp.co.jp/article/OPINION/20090725/334475/

[13] IT Pro News, "Android terminal is not a telephone, but a "Cloud device"," a keynote lecture at ABC 2009, Fall 2009 http://itpro.nikkeibp.co.jp/article/NEWS/20091130/341285/

[14] IT Pro News, the souvenir to the participants was a "PDC model" laptop: http://itpro.nikkeibp.co.jp/article/NEWS/20091120/340809/

[15] Fujio Maruyama, "Creation process of the Cloud and its technological characteristics," the journal of the Information Processing Society of Japan, Vol.50, No.11, 2009

[16] "IBM and Google support universities using high-speed parallel computing," ZDNet Japan, October 9, 2007 http://japan.zdnet.com/news/software/story/0,2000056195,20358216,00.htm

[17] Makoto Tachikawa, "PC grid computing – efficient use of prevalent PC power: an abundance of computing resources supply to society," Science & Technology Trends, No. 54, September 2005

[18] General Services Administration's Apps.gov: https://apps.gov/cloud/advantage/main/start_page.do

[19] "Investigation Concerning the Follow-up of 3rd Basic Program for Science and Technology–Outcome of Governmental Investment", NISTEP REPORT No. 134, p. 128–137, (2009)

[20] Taiwan Cloud Computing Consortium: http://www.taipeicloud.com/

[21] M. Watari, "Trends of Grid Technology – Can It become the core technology for the next generation Internet utilization," Science & Technology Trends, September 2002

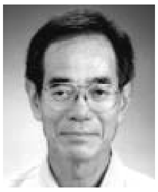
[22] Martin Rinard, etc.,"Enhancing Server Availability and Security Through Failure – Oblivious Computing," Proc. 6th Conference on Symposium on Operating Systems Design & Implementation, 21 - 21, 2004

[23] "Amazon to start providing a Cloud service "Virtual Private Cloud"," CNET Japan, August 27, 2009: http://japan.cnet.com/news/ent/story/0,2000056022,20398965,00.htm

[24] K. Iwano, "Scope of Business Ecosystem Provided by the Cloud," CIO Magazine, p.16-21, April 2010

[25] N. Yajima, "No IT Engineer Required in Cloud Age?," ITPro, May 7, 2010:
http://itpro.nikkeibp.co.jp/article/Watcher/20100507/347748/?ST=cloud&P=1

Profile



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4

The New Trends in Next Generation Biomimetics Material Technology: Learning from Biodiversity

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1 Introduction

1-1 Monozukuri Technology Inspired by Nature

The importance of "Learning from Nature" is a prevailing knowledge in each field of science and technology. Since the turn of the century, the research and development on the nature-inspired manufacturing technology, generally referred to as "biomimetics," have been coming to the fore in Europe and the United States. For example, National Geographic Magazine put together the feature stories on "Nature-inspired Design" in its April 2008 issue. It presented, under the title "Biomimetics: Design by Nature," a variety of research and development projects now in progress, such as the fluid-dynamically fuel-efficient car design and the paint that can be cleaned by rain. Some of the contents of these feature stories were presented in detail in Peter Forbes' book "The Gecko's Foot: Bio-inspiration—Engineering New Materials from Nature" published in 2005 (Japanese translation by Michiyo Yoshida was published from Hayakawa Publishing Corporation in 2007). More recently, the importance of "Learning from Nature" is recaptured from the viewpoint of energy and environmental concerns. For example, in 2008 the incorporated nonprofit organization Biomimicry Institute hosted a conference titled "Biomimicry's Climate-Change Solutions: How Would Nature Do It?" This NOP was established by Janine Benyus, the author of "Biomimicry: Innovation Inspired by Nature" (Japanese translation by R. Yamamoto and M. Yoshino was published by Ohmsha Ltd. in 2006). The concept of "Nature's 100 Best" (Innovation Inspired by Nature) propounded by them has been gaining attention, and presented both in COP9 (The 9th meeting of the Conference of the Parties of Convention on Biological Diversity) held in Bonn in 2008 and the UNEP (United Nations Environmental Programme) held in 2009.[NOTE 1] The details of "Nature's 100 Best" is presented at ZERI Foundation (Zero Emission Research Initiative Foundation)'s website.[NOTE 2]

The terms such as "biomimicry," "bioinspiration," and "bioinspired" are derived words from "biomimetic," and, as is described later, "bioinspired" is sometimes used to connote a presumed heir of the word biomimetic. In this article, however, "biomimetic" is consistently used as it is the origin of these words and has comprehensive meanings.

1-2 Growing Interest in Biomimetics

In the backdrops of the growing interest in nature-inspired manufacturing, there has been a "changing tide" of biomimetics research that is rapidly developing and forthcoming across the period spanning from the end of the previous century to the current century. According to ISI Web of Knowledge, the number of papers relating to biomimetics has shown a steep increase since the turn of the century (See Fig.1).

A journal specializing in this field "Bioinspiration & Biomimetics" came out in 2006, and major academic journals such as PNAS[NOTE 3] and MRS [NOTE 4] had feature issues on biomimetics. The number of international conferences relating to biomimetics is steadily on the rise. The National Academies (U.S.) has taken up biomimetics as one of the challenges to be addressed, and issued in 2008 a proposal for the science and technology policies entitled

[NOTE 1] UNEP:United Nations Environment Programme
[NOTE 2] ZERI:Zero Emission Research and Initiative
[NOTE 3] PNAS:Proceedings of the National Academy of Sciences
[NOTE 4] MRS:Materials Research Society

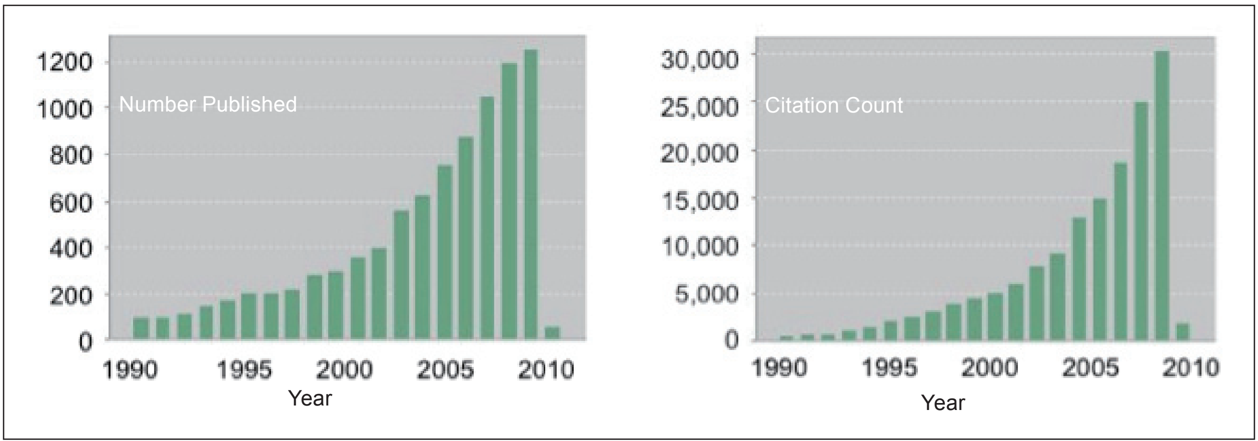

Figure 1 : Trend of Published Papers in Biomimetics and Related Fields

Prepared by the STFC

"Inspired by Biology: From Molecules to Materials to Machines," wherein super water-repellent surface materials that mimic lotus leaves, adhesives that mimic gecko fingers, and photonic materials inspired by Morpho butterflies are presented as examples of "Next-Generation Bioinspired Materials." In view of promoting academic-industrial alliances and industrialization in this field, a full-scale international convention, "International Industrial Convention on Biomimetics," is scheduled to open in Berlin in March 2011 under the auspices of the Federal Republic of Germany.

2 History of Biomimetics Research

Why has biomimetics research, with its long history, been regaining attention as a new trend since the turn of the century? Figure 2 gives an overview of the history of biomimetics research from the viewpoint of the sizes of research objects and fields of interests.

2-1 The Dawn of Biomimetics Research

The term "biomimetics" (in Japan, the term is translated literally as "Imitation of Living Things") was proposed by German-American neurophysiologist Otto Schmitt in the latter half of the 1950s.[1] Schmitt is known as the inventor of the Schmitt trigger, which

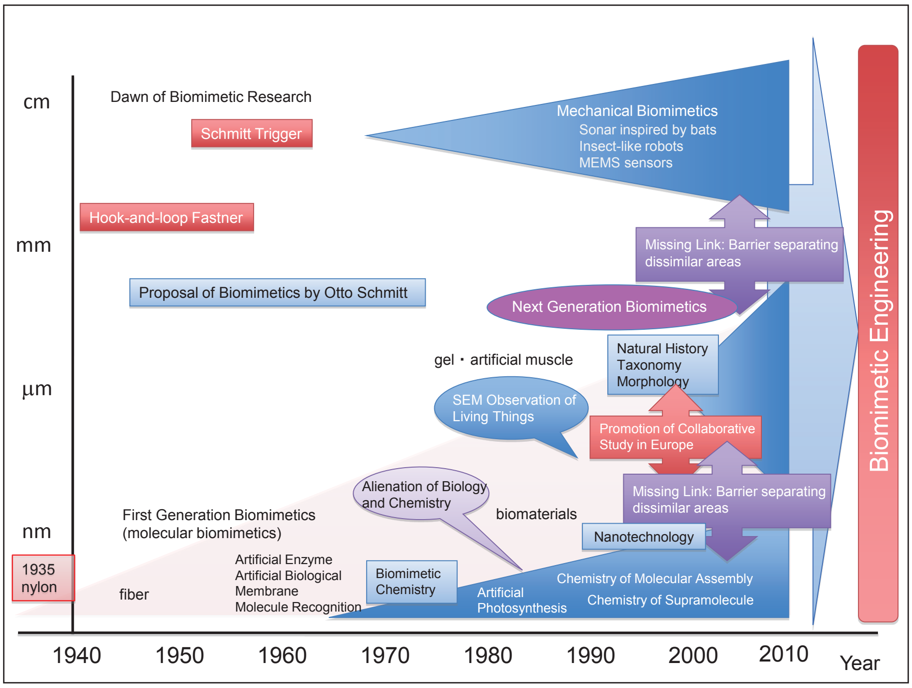

Figure 2 : History of Biomimetics Research

Prepared by the STFC

is an electric circuit used to eliminate superimposed noise from an input signal and transforms it into a series of rectangular pulses. This invention was an example of simulating signal processing taking place in the nervous system. The biomimicry approach in material research dates back further: VELCRO® (known as “magic tape” in Japan) is considered to be an early example of biomimicry realization, and the light-reflecting plate embedded in the center line of roads (raised marker, or “Cats Eye”) is also said to be an exemplification of biomimicry technology.

2-2 Appearance and Decline of Biomimetic Chemistry: The First Generation Biomimetics Research

In the 1970s, biomimetics research came along in the fields of chemistry, as “Biomimetic Chemistry,” aiming at molecular-level emulation of enzymes and biomembranes. Around the same period, it became apparent that the X-ray structural analysis had the capability to provide reaction site information on enzymes (i.e., biocatalysts), enabling molecular-level elucidation of biological reactions using techniques of organic chemistry. What was essential in unraveling biological events from chemical standpoints in view of engineering applications was the biology-chemistry collaboration. The artificial photosynthesis research that became active in the 1980s laid the foundation for dye-sensitive solar cells, and the actuator research, using gel, brought about such inventions as synthetic muscles.

However, the evolution of molecular biology subsequently turned the mainstream of biology toward the elucidation of life phenomena, where the gene plays a central role. The mainstream of biomimetic chemistry research—an area best described as “biomimetics of molecular systems”—began to show tendencies, accompanied by the rise of molecular electronics research in the latter half of the 1980s, to distance itself from biology, and headed toward the chemistry of molecular assemblies and supramolecules. Entering the 1990s, in spite of the prevalence of the idea “Learn from Living Things,” the opportunities for linkage with biology, in effect, almost disappeared. Even the term “Biomimetic Chemistry,” which represented an academic field, became almost extinct in the wake of the shift of focus toward molecular nano-technology and nano-biology. The idea “bioinspired —taking cues from living things and surpassing them—became mainstream, marking the decline of the first generation biomimetics, or biomimetic chemistry.

2-3 The Development of Mechanical Biomimetics

In the 1970s, biomimetics research also blossomed in such fields as mechanical engineering and fluid dynamics; developments in these fields included robots that mimicked movement of insects and fish, and the sonars and radars that mimicked echolocation capabilities of bats and sensory hairs of insects. Mechanical biomimetics research has continued without decline up to now mainly in such areas as military industries, railways and ships, and aeronautics industries. They have also had an impact on such cutting-edge fields as micromachines and MEMS.[NOTE 5] In present-day Japan, the term “biomimetics” seems to have more of a connotation synonymous with robotics research.

2-4 The Rise of Material Biomimetics

As exemplified by the proposal made by the National Academies (U.S.) in 2008, i.e., “Next-Generation Bioinspired Materials,” with the coming of a new century, new trends of biomimetics have been gaining focus in material research centered in Europe and the United States. A movement is afoot to bring the research results into practical use.

In many cases, the surfaces of living things are characterized by hierarchical structures in dimensions ranging from nanometers to micrometers. These ranges of dimension are the targets of nano-technology. One of the outstanding characteristics of nano-technology, as compared with conventional technologies, is the fact that its objectives have dimensions that require observation and analysis using electron microscopy, and this very fact embraces possibilities to provide a platform for biology-material science collaborations through the use of common methods for observation and analysis. Electron microscopy has revealed the hierarchical structures of living things that range from nano- to miro-meters range. Inspired by the knowledge of the hierarchical structures in the surfaces of living things, as revealed by the researchers of morphology and taxonomy, the development of nano-technology in the last decade has enabled the material researchers to artificially

[NOTE 5] MEMS:Micro Electro Mechanical Systems manufacture similar structures and they are in the process of artificially realizing functions that originate from the structure. Researchers in Europe, especially Germany and the U.K., have been the driving force of these researches.

As described earlier, the first generation biomimetics, or Biomimetic Chemistry, was born thorough a collaboration between biology and organic chemistry that aimed at mimicking living things on the molecular level, and X-ray structural analysis built a momentum for this trend. In contrast, the material research, or new generation biomimetics, are considered to have been created through collaborations among natural history, biology, and material nano-technology, where electron microscopy and microfabrication technology provided the common platform. The characteristics of nano-technology in Europe are symbolized by the term “Nano meets Bio.” That is, the objective is the fusion and linkage between dissimilar fields. For example, in the research carried out in German universities, linkage between dissimilar fields has become the prerequisite for gaining research funding.[2] The reason that signs of forthcoming activities in new generation biomimetic material research appeared first in Europe can be ascribe to a cultural background that values cross-fertilization as well as to the European science and technology policies that proactively look to fusing together dissimilar fields.

3 Trends in the Research of Next Generation Biomimetics Materials

In this chapter, some of the success stories of biomimetic material research are presented. These challenges have their sights set on practical applications and the description is centered on how the collaboration between biology and material nanotechnologies was carried out.

3-1 The Superhydrophobic Material Inspired by Lotus Leaves, and the Research Derived from It

The wettability of a solid surface with water is governed by the material’s intrinsic degree of hydrophilic/hydrophobic property (surface free energy) and surface profile. In general, such materials as silicone, wax, and fluoride compounds have a low level of surface free energy, and show hydrophobic properties because of the poor hydrophilicity. A hydrophobic surface with rough surface irregularities has an augmented actual surface area (Wenzel state), and the small void formation due to the surface irregularities hinders water from entering (Cassie-Baxter state). This makes the surface even more resistant to wetness.[3]

Professor Wilhelm Barthlott (a botanist at the botanical garden in Bonn University) found that, on the surface of lotus leaves, the surface microstructure and secretion of wax-like compounds have a synergetic effect that produces superhydrophobic property and is self-cleaning.[4] Arrays of bumps the size of several micrometers are found on the surface of lotus leaves, and, protrusions of microcrystals made of wax-like material form arrays on the surface of each bump. The fractal undulating structure, with the hierarchical structure described above, provides the surface of lotus leaves with such super hydrophobic property.

Surface microstructure brings about hydrophobicity, resulting in a cleaning effect, which is called the Lotus-Effect® (a trademark of Bonn University). Bonn University carried out collaborative research with a plural of companies and developed a paint called “Lotusan”—nanoparticles (e.g., hydrophobic silica) are dispersed in a binder material. Several companies including Evonik (former Degussa) have put the paint into commercial production. The discovery of the lotus effect can be counted as one of the most classical successes in new generation biomimetics research, and it was brought about by biology-material science-industry collaborations. Inspired by this success, cases of technological developments are underway in search of effects similar to Bonn University’s. These include the textile spray (MincorR TX TT, BASF), coating material (Nikka Chemical), hydrophobic polymer (Lexan, GE), convexo-concave surface formation by means of plasma CVD technique (Nagoya University), and highly water-resistant cosmetics (Kanebo).

The discovery of the lotus effect induced surface-structure research on living things that dwell in aquatic environments. The petals of roses, clivias, and sunflowers show superhydrophilicity, but at the same time they have so strong an adsorption power to water that they hold water drops even if they are held upside down. Rose petals, as well as the surface of lotus leaves, have hierarchical structures, and the surface of bumps (10–20μm) is covered, not by the protrusions, but by the concatenation of pleats with the repetition period of several hundred nanometers.

These pleats are considered to be the source of strong adsorptive power,[5] and they originate from van der Waals force inherent to the microscopic surface structure. Synergetic coexistence of hydrophobicity and adsorptivity is called the "rose petal effect," and the polystyrene nanofiber with its hollow structure represents a material that exhibits this effect.[6]

The materials covered by dissimilar patches of surfaces—ones with hydrophobicity and others with hydrophilicity—were also developed through a collaboration of biologists and material scientists. Professor Andrew Parker (a biologist at London's Natural History Museum) studied the Stenocara gracilipes—a beetle inhabiting in Namib Desert—and elucidated the mechanism the beetle uses to drink water by gathering tiny water drops of morning dew. Living in the desert near the sea, the beetle stands straight for a while with its head down every morning and evening. Its body surface is covered with a patchwork of dissimilar surfaces—tiny hydrophobic bumps the size of micrometers, and hydrophobic patches in between that are one-tenth the size of the bumps and characterized by a convexo-concave structure. The dewdrops adsorbed in the hydrophilic surface patches gradually grow, their weight causes them to roll down along the hydrophobic surfaces, and they gather into the mouth of the beetle standing with its head down.[7] Professor M. Rubner and R. Cohen at Massachusetts Institute of Technology developed water-gathering material that mimicked these beetle surface skins. They used a thin-layer manufacturing technique called the Layer-by-Layer method to develop water-repellent property, an array of silica microparticles (hydrophilic bumps) on a solid substrate, and the area in between was covered by water-repellent fluoride compounds. Dews are trapped and grown to water drops on the surface of silica particles (hydrophilic adsorption sites) and these were successfully gathered into one location through the channels formed by the surrounding water-repellent smooth surface.[8] They consider it probable that a scaled-up version of this type of surface could be used as a device for dew collection, to secure water resources in dry regions and areas with poor fluviatic resources.

As described later in section 4-6, the manufacturing techniques also present major research challenges in the development of biomimetic materials. Among them, the self-organization technology has become a focus of attention. An attempt has been made to make a surface material that is both superhydrophobic and strongly adsorbing by actively introducing adsorbing sites in the water-repellent surface using the self-organization phenomena and a simple electroless plating technique. A polymer spike—metallic microdome composite—was manufactured. This material is characterized by the coexistence of superhydrophobicy (due to polymer spikes) and strong hydrophilicity, allowing a large contact angle and giving strong absorptive power to the water drops that came in contact with it.[9] That is, this material was created by a combinational approach involving biomimetic material design and a manufacturing technique employing self-organization. In addition, incorporation of a metal for additional functions made it a hybrid material.

In recent years, China has had a brilliant track record in research and development of biomimetic superhydrophobic materials. The researchers in China are trying to find an interrelation existence between the various types of surface structures of living things and their functions. These include the oil-repellent property of fish scales, water-collecting material inspired by spider webs, and water-repellent property inspired by mosquito eyes, butterfly wings, and legs of water striders.[10]

3-2 Growth of Material Development Inspired by Sharkskin Riblet

The "swimsuit row" that involved people concerned in competitive swimming in 2008, just before the Beijing Olympics, was, from the point of view of material development, a major accomplishment for Speedo's biomimetics strategy—although it was accused of being "high-tech doping" in some quarters. Speedo's LZR Racer®, and its prototype FASTSKIN-FSII®, achieved high-speed swimming by using a hollow-fiber textile, in addition to the weight saving accomplished through superhydorphobic treatment. It was a verified knowledge that a water-repellent surface had a resistance mitigating effect to laminar flow, and it was theoretically predicted that it had a similar effect to turbulent flow as well. One characteristic of Speedo's swimsuits that attracted attention was the fact that they had a fish-skin riblet structure on their surfaces. The riblet structure is characterized by repetitive grooves in several tens of micrometers to below one-millimeter intervals,

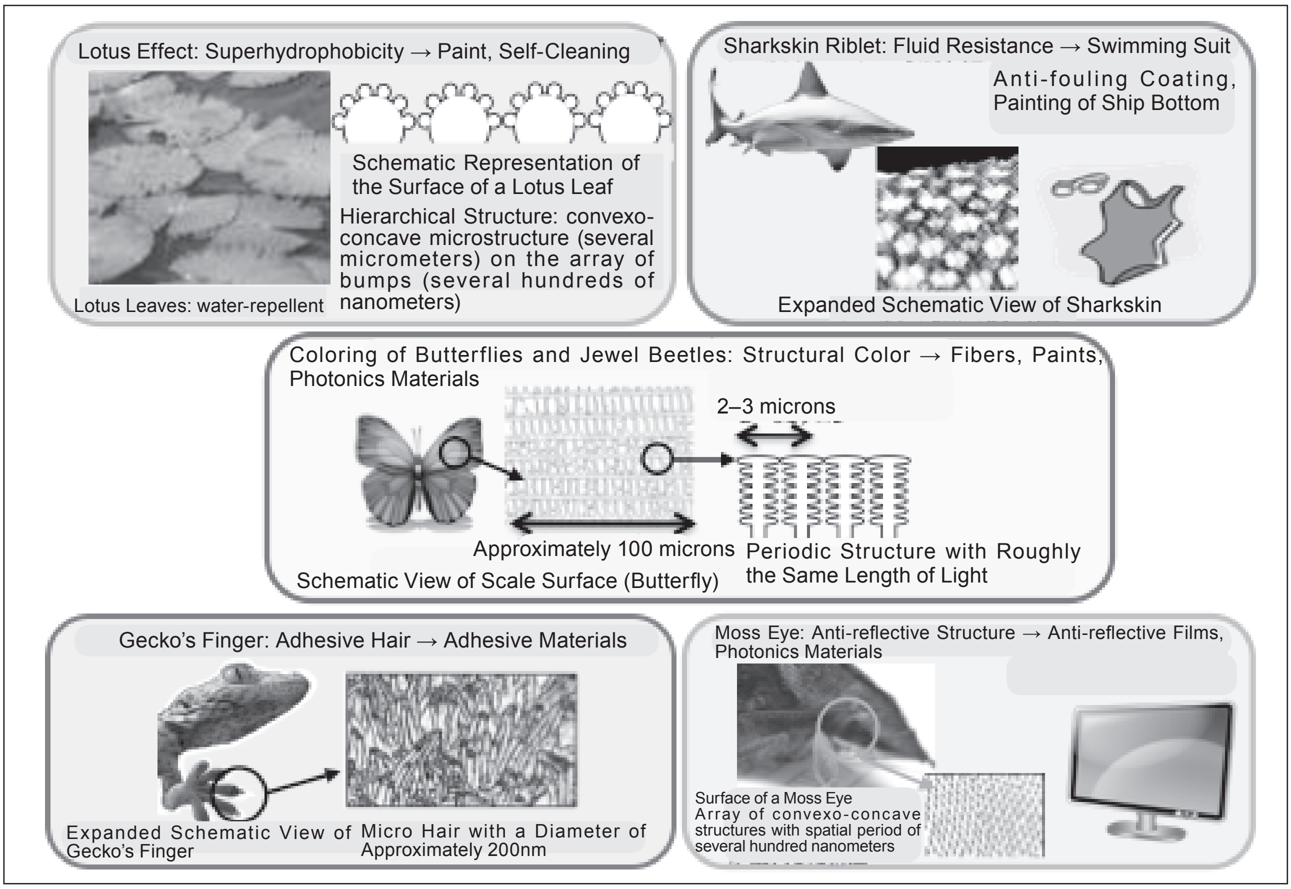

Figure 3 : Success Examples of New Generation Biomimetics Material Research

Prepared by the STFC

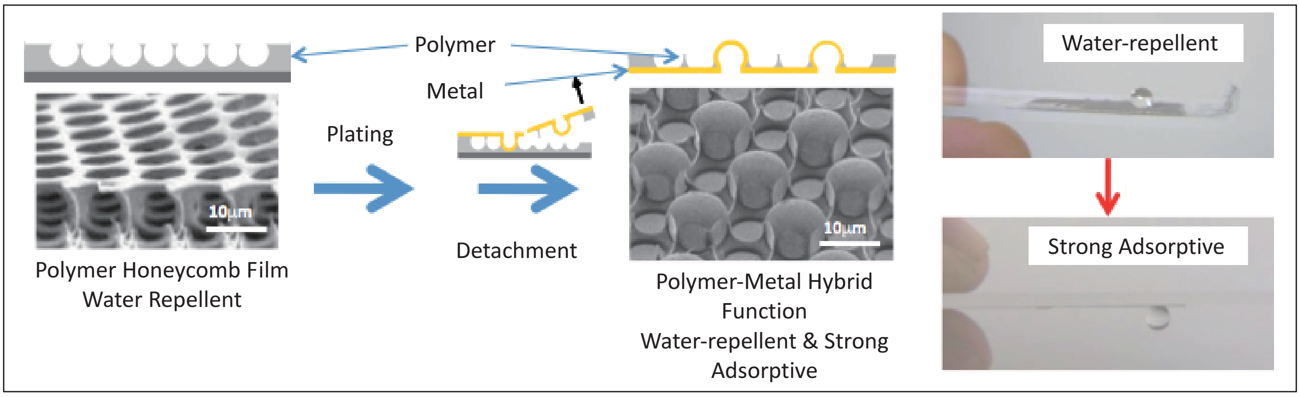

Figure 4 : Example of Biomimetics Material That Incorporates Self-Organization

Prepared by the STFC

and the introduction of such structure had been long known to reduce friction resistance with a fluid. The riblet films developed by 3M have been applied to the outer surfaces of racing yachts (e.g., America's Cup) and Airbus industries' passenger aircrafts, and they have been reported to have improved cruising velocity by several percents and enhanced fuel efficiency.

In recent years, the riblet structure has also attracted attention for its anti-fouling effect. The conventional method of choice to deter attachment of marine organisms (i.e., acorn shells and algae) to the ship bottoms and cooling water channels of power plants has been the use of TBT (tributyltine). However, because TBT is one of the hormone-disruptive substances (so called "environmental hormone"), the International Maritime Organization decided to make a blanket ban to be implemented by 2008. Therefore, TBT-free anti-fouling methods, especially an effective use of surface structure, are under investigation. Solid surfaces with surface tension in the range between 25 and 0 mN/m are known to have a physical effect to hinder biofouling. A research group at Hochschule Bremen reported that a surface made of soft silicone with a riblet structure on it (riblet interval: 76μm, surface tension: 25mN/m) had an effect of reducing nearly 70% of an acorn shell attachment as compared to a flat and smooth surface.

In another development in Europe, "Surface Engineering for Antifouling—Coordinated Advanced Trainin (SEACOAT)" started in January 2010 as one of the European Frame Work Programs (FP7). As part of this program, a joint effort between industries and academia aiming at the anti-fouling material development utilizing nano-/micro-structure has started. The multi national research team consists of 17 organizations from countries including the U.K., Germany, and Switzerland.[11]

In recent years, the riblet structure has attracted attention in applications other than marine anti-fouling. Professor Anthony Brennan at Florida University and other researchers have focused attention on the antibacterial properties of the riblet structure. They developed a medical film (Sharklet TM) and aim to use the film in such applications as the wall material of medical facilities and medical devices such as catheters.

The website of the National Museum Director's Conference (U.K.) states that the sharkskin riblet was an accomplishment of joint-research with the museum for the 2008 Olympic games, and it reduced fluid resistance by three percent. Fiona Fairhurst, a Speedo's "Biomimetician" and the developer of FASTSKIN®, was recommended as a candidate for the European Inventor of the Year Award in 2009, and she expressed her appreciation to the members of London's Natural History Museum for their corporation. This is a symbolic episode indicating that the collaborations between natural history and nanotechnology are absolutely necessary for the new generation of biomimetics research and development.

3-3 Structural Color Materials Inspired by Butterflies and Jewel Beetles: Database Compilation of Relevant Information

The body color of jewel beetles and morphos, with characteristic metal luster, is called a "structural color." Structural colors develop their peculiar tints not through light absorption by pigments or colorants, but by a microstructure with the dimensions comparable or shorter than the wavelength of light. Therefore, structural colors are free from such problems as fading and degradation. A variety of mechanisms is known to be the sources of structural color expression: thin layer interference, multilayer interference, interference caused by micro-scale grooves and bumps, and scattering and diffraction of light caused by arrays of microparticles. Material development research inspired by structural color expression of living things are actively underway: collegiums on structural color are being held under the leadership of Professor Pete Vukusic at the physics department of Exeter University (U.K.) and Professor Shuich Kinoshita at Osaka University (Japan), and these provide useful information regularly on this subject. Structural color also presents itself, other than on the body surface of living things, in minerals (e.g., opal) and colloidal crystals. The applications of structure color cut across a variety of industrial sectors, including paint, cosmetics, jewelry, textiles, and photonic crystals. The structural colored fiber morphotex is a world-renowned accomplishment, and was developed through the collaboration of three companies: Nissan Motors Co., Ltd, Teijin Fibers Ltd., and Tanaka Kikinzoku Kogyo. Recent research has further pointed out potential use of high-refractive index organic materials for structural color expression.[12]

Professor A. Parker and et al at London's Natural History Museum published the paper "The reviews on diversity and evolution of butterfly's photonics structures, with mentions to the achievements done by John Huxley" in the Proceedings of the Royal Society.[13] They considered that the anatomic and comprehensive descriptions of the photonic structures of butterfly wings would contribute to potential applications of biomimetics, and compiled the review based on the unpublished electron micrographs taken by the late Dr. John Huxley as a useful database to understand diversity and evolution. The publication of the vast amount of inventory stored in the museum (a catalog of all living things inhabiting a region, and investigation results for making such a catalog) and the compilation of the data into a database, from the viewpoint of anatomical structures and functionality, was a worthwhile endeavor for the next generation biomimetics research.

3-4 Adhesive Materials Inspired by Gecko Legs

The biomimetics of gecko lizards' fingers have been, as well as the lotus effect, another success stories of biology-material science collaboration. In June 2003, BBC News (online) published the article "Gecko inspires sticky tape," about a research group, headed by Professor Andre Geim at Manchester University, that successfully developed an adhesive-free adhesion tape that mimicked the microstructure of a gecko finger. It is a wonder that a gecko can crawl on walls and ceilings considering that it does not secrete a sticky substance on its fingertips. A gecko's fingertips have traces of cracks (lamellars) and thick growth of several hundreds of thousand of bristly hairs (seta) inside the cracks. At the tip of each bristly hair, with a length around 100μm and diameter around 5μm, the hair ramifies into several hundreds of split ends, with a dish-like structure (spatula) on each end. Each spatula has an approximate diameter of 200nm. According to the biological hypothesis of Keller Autumn et al,[14] the adhesive force of the gecko fingertips originates from van der Waals force between the surfaces of the dense growth of hierarchically structured microscopic bristly hairs and the wall surface. The research groups of Ronald Fearing at UC Berkley[15] and Andre Geim[16] reconstructed a surface with a dense growth of bristly hairs on it, whereby a microfabrication technique using AFM (Atomic Force Microscopy) chips and the nanoscale pores of anodized alumina was used. They not only elucidated the adhesion mechanism of gecko fingers, but also succeeded in developing an adhesive-free adhesion material (i.e., "Gecko Tape"). Subsequently, a paper reported that the solid surface with its dense growth of bristle hair made of carbon nanotube also exerted a strong adsorptive power.[17] Research and development efforts toward practical use of this technique have already begun, and the objectives include an adsorbent agent used in recyclable construction materials. A gecko-type robot capable of moving along walls has been developed. It uses a gecko tape as an adsorptive agent and is expected to have a range of applications in both civilian (such as disaster-relief operations) and military uses.[18] Currently, the efforts toward practical use of this type of robot are being stepped up notably in the United States.

3-5 Anti-reflective Materials Inspired by the Moss-eye Structure

In the 1960s, C. G. Bernhard et al (Karolinska Institute, physiological department) reported that the surface of a moth's compound eye is covered with arrays of protrusion structures approximately 100nm in size.[19] Subsequently, in the early 1980s, S. J. Wilson, M.C. Hutley, et al (optics division of U.K. National Physics Laboratory) made clear that a periodical array of convexo-concave structures (moth-eye structures) had the effect of gradually changing refractive index in the direction normal to the surface, resulting in a non-reflective surface.[20] This structure, in effect, eliminates the clearly defined reflecting plane (step change of refractive index) and suppresses light reflection. The complex eye with such internal structure enables the moth to fly at night, and, because the light reflection from their large eyes is suppressed, is believed to hinder predators (e.g., birds) from finding them.

The anti-reflective film, with its moth-eye structure, received attention from early on in the research and development of optical materials. Holotools GmbH (Germany) used the interference lithography technique to produce repetitive patterns with the period from 100nm to 100μm on a solid substrate. Using this technique, the company manufactures transparent polymer films with their surfaces covered by the moth-eye structure, and provides the product for use as a large-area anti-reflective film of a display device. Recently, Mitsubishi Rayon Co. Ltd. succeeded in incorporating moth-eye structure on the surface of a transparent polymer film (the commercial product has reflectance below 0.1%, and total transmission of 99.6%), whereby anodized alumina—nanoscale pores are formed regularly in self-organized fashion—was used as a die. In 2009, Oji Paper Co. Ltd. succeeded in establishing the technique to coat a surface on which a single layer of microparticles (25–1000nm in diameter) are being arrayed in high precision, and this led to a successful manufacture of the dot-type periodic microstructure.

The moth-eye structure also gains attention from a viewpoint of enhancing solar cell efficiency.[21] J. G. Rivas et al (Institute for Atomic and Molecular Physics (AMOLF), the Netherlands) discovered that a fabrication of moth-eye structure rods on the surface of a GaP substrate drastically reduces the wide wavelength range of light reflection (from visible to near-infrared region). In Japan, Mitsubishi Electric Corporation has achieved 18.6% of photoelectric conversion efficiency in its polycrystalline solar cells: to reduce surface reflectance, a honeycomb convexo-concave structure was introduced on the surface of the polycrystalline silicone solar cells using laser patterning and wet etching techniques. Mitsubishi plans to put it to practical use in 2010.

3-6 Low Friction Materials Inspired by Sandfish

Scincus scincus, a lizard that belongs to Pholidota skinks, is an inhabitant of deserts in North Africa and Southwest Asia, and is called a "sandfish" as it dives into the sand and moves below the surface in a swimming-like motion. It is around 15cm in length, goes under the "sea of sand" to the depth of several centimeters, and it can "swim" at a speed of 10–30cm/sec.[22] Professor Ingo Rechenberg at Berlin Institute of Technology found that the sandfish's scaled skin had a even smaller friction coefficient than those of polished steel, flat and smoother glass, Teflon, and high-density nylon surfaces, and showed hardly any sign of wear after it suffered abrasion with sand. The scales of a sandfish consist of sulfur-rich glycosylated ceratine, and do not contain inorganic materials such as silicates. Having ceratine as the main component, the scales have microstructures on their surface and these produce peculiar tribological properties. Professor W. Baumgartner et al coated a polymer film with the ceratine extracted from the scales, and found that the surface showed similar properties as the scales. Using atomic force microscope measurements, they showed that there is hardly any attractive force between the surfaces of the scales and a silicon chip. Rechenberg et al verified that the falling angles of sand on a sandfish skin are lower than those on glass, nylon, Teflon, and steel surfaces, which exemplified the very low frictional resistance. On the other hand, the sandfish skin has a higher abrasion resistance than those surfaces of steel and glass. The scale of a sandfish is characterized by an array of "nanothresholds" with sub-micrometer height, stretching like mountain ridges with several micrometers spacing in between. Rechenberg et al suggested that the static electricity generated by frictional electrification between the "threshold" and sand grains is the probable origin of friction reduction, i.e., the static charge produced repulsive force between the scale and sand grains. The predator of sandfish—the snake—also has a skin with a very low-friction surface, presenting an investigation object for biomimetics research.[23]

In the program "Abrasion resistant surface coating mimicking the sandfish's epidermis" under the guidance of Professor W. Baumgartner at RWTH Aachen (Germany) —included in the doctoral research and educational program called BIONIC Graduate[24] —research and development is underway to analyze chemical and physical composition of the sandfish's epidermis, and coating processes of metal, glass, and polymer surfaces using these sandfish skin components. The final objective of the program is to develop a low-cost coating technique that realizes an abrasion-resistant surface inspired by the tribological properties of the sandfish's epidermis structure. Scar-resistant front glasses and lubricant-free low friction ball bearings are among the accomplishments to be expected from the program.

Recently, X-ray footage was taken of a sandfish "swimming" in the fluidized sea of sand, undulating and snaking its body, without using the four legs. The tribological effects of the scale surface, characterized by the microscopic structure, on the sandfish's fluid dynamics while it is swimming in the "fluidized media" of fine solid particles have become steadily apparent. The research on the "swimming" of a sandfish has the potential to provide new links between the material-oriented and mechanics-oriented biomimetics.

3-7 Research on Tribology Inspired by the Evolutional Struggles between Insects and Plants

Professor Stanislav Gorb et al at Kiel University (zoological department) have been advancing systematic research on the surface tribology of insects and plants. For example, Tettigonia Viridissima (a grasshopper) has a tile-like arrangement of hexagonal patterns on the tips of its legs (see Fig. 5). Similar microscopic patterns were fabricated artificially on the surface of silicone rubber using microfabrication technology and their frictional properties were measured.[25] The results showed that the patterned surface guaranteed stable mobility in both dry and wet conditions: when the surface is dry, it enabled smooth movement completely eliminating stick-slip motions, and when wet, it had the effect of avoiding hydroplaning, or side skids.[25] As the result of undergoing evolution and adaptation in close connection with insects, some of the plants also have interesting surface mirostructures. Dr. Elena Gorb, a botanist, revealed that Sarawak's pitcher plant, a insectivorous plant, has types of mirostructures on its outer and inner surfaces,[26] making the surface quite slippery to many insects. One of the inner surfaces used to catch hold of an insect, called a slippy zone, is observed to have a structure similar to the superhydrophobic fractal structure that appears on the surface of alkyl-ketene dimer crystals[27]—a sizing agent used to modify paper surfaces. This is quite an interesting finding from a viewpoint of material science.

Evolution processes have bestowed a manifold of functions to the legs of insects. A beetle (Pameridea roridulae) can prey on a fruit fly trapped on the surface of Roridula gorgonias (a plant that secretes sticky substance) without being itself trapped by the stickum. The legs of beetles have a grease-like cuticle epithelium that can partially peel off and acts as a "sloughing-off" layer. This layer is believed to be instrumental for an insect to escape from the sticking material secreted from a plant.[28] This research has been advanced as a part of the Germany priority program "Biomimetic Materials Research: Functionality by Hierarchical Structuring of Materials (SPP 1420 priority program)."

3-8 Sensor Materials Inspired by the Sensing Ability of Insects

In recent years, the research on sensors using new biomimetic materials is being carried forward, wherein biologists are playing the central roles. Cupedidae (Melanophila) is known to deposit its eggs to a vacant ruin after a bush fire. The lack of predators is believed to induce the insect to lay eggs in the fire ruins. Cupedidae has a highly sensitive infrared sensor that can detect a bush fire several tens of kilometers away, and Professor H. Schmitz et al at Bonn University (zoological department) elucidated that it is a type of mechanosensitive sensor.[29] Multiple arrays of spherical sensory cells (sensillum) are arranged on the backs of complex eyes, and each cell has sensory hairs covered by hard cuticle walls before being connected to a neuron cell (see Fig. 6). A structure consisting of narrow canals is in place inside the cell, and the canals are filled with liquid. Irradiation of infrared light (wavelength 3μm) causes an effectively thermal expansion of the liquid inside the canal and thus compresses the sensory hairs, resulting in a conversion to mechanical stimulus that is transferred to the nervous system.

Based on these findings, Bonn University advanced a joint research with CAESAR[NOTE 7] at PMI [NOTE 6] and has developed a prototype for a robust infrared sensor that requires no cooling device. The sensor has a very simple operating principle: thermal expansion of liquid (water) confined in a tight space is detected by a condenser.

The cricket is known to have the ability to detect the approaching predator by sensing the change of airflow. The growth of aeroscepsy hairs located at the rear tail of the body is actually a sensillum array[30] (different size of sensory hairs are arranged to cover a wide frequency range) to effectively pick up a signal among noises (Fig. 7). The aeroscepsy cell of the cricket has an energy threshold comparable to the Brownian motion energy (kT), and the cell is said to have the ultimate efficiency as a sensory organ.[31] A MEMS sensor that mimics the sensory hair of the cricket is under development by a joint research team consisting of the group led by Professor J. Casas at Tours University (entomology department) and the group led by Professor G. Krijnen at Twente University (Transducers Science and Technology Group ("MicMec")).[32]

The accomplishments from the collaborative research were presented at the international conference held in Dresden in 2009 ("1st Natural and Biomimetic Mechanosensing"). This conference was held under the initiative of the European consortium called "CILIA."[NOTE 8] Other presentations in the international conference relating to the biomimetics of cricket included the polymer sensor film that mimicked the cricket's eardrum.[33]

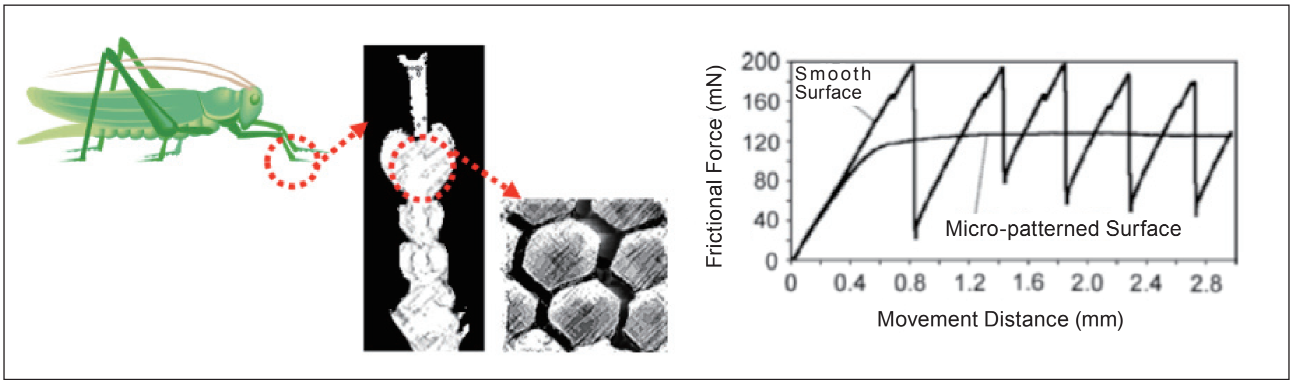

Figure 5 : Tribology of Insects' Legs

Prepared by the STFC

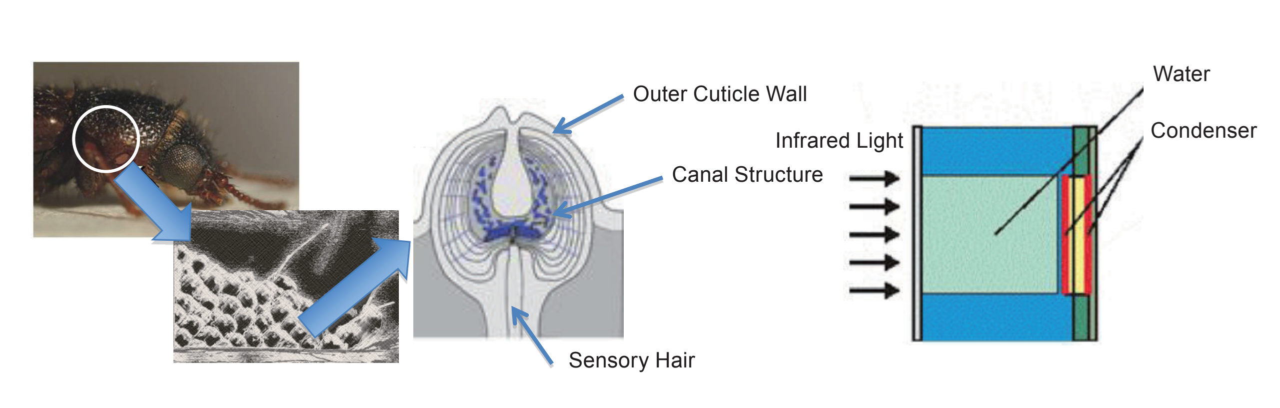

Figure 6 : Schematic Diagram of an Infrared Sensor Inspired by and Mimicking the Infrared Receptor Arrays of Cupedidae

Prepared by the STFC

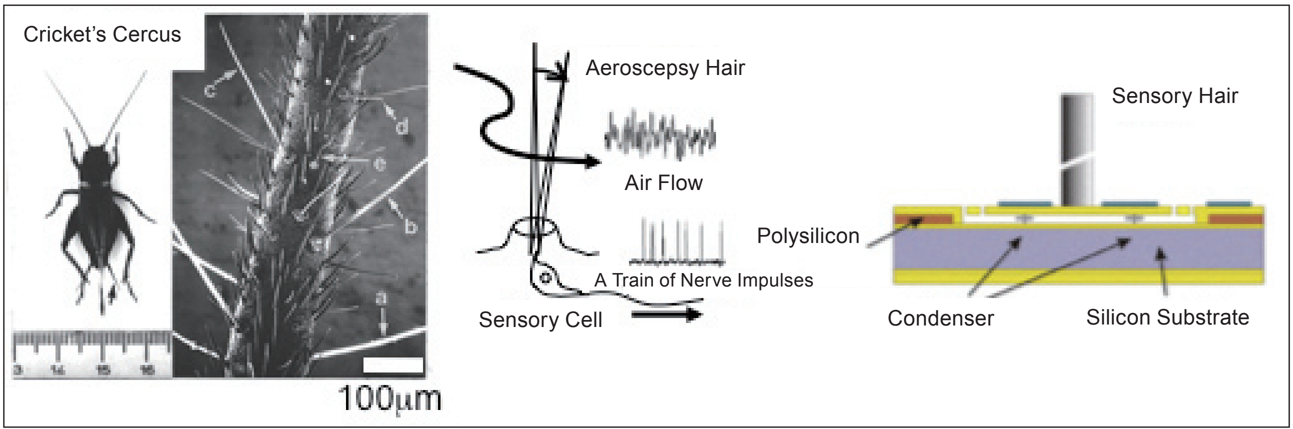

Figure 7 : MEM Sensor Inspired by the Flow Sensor of Cricket

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4 Important Points of New Generation Biomimetics Research

In this chapter, the author summarizes important points in the new generation biomimetics research, paying due consideration to the examples of success in Europe.

4-1 Point 1: Evolution and Adaptation of Living Things Provide Good Models for Material Design: Diversity of Living Things Translates into Diversity in Material Designs

Professor S. Gorb at Kiel University (a natural historian and one of the leaders in "Bio-tribology"[34]) gave, in his book Attachment Devices of Insect Cuticle, a systematic and comprehensive description of the adhesion mechanism of insects' legs in line with evolutional grouping. The book makes it clear that the attachment mechanisms could be classified into several categories: those that do not require secretion of sticky substances (van der Waals type such as a gecko), those that use nail-like hooking structure, and so forth. The book also makes clear that what attachment mechanism an insect selects does not depend on the evolutional lineage of the insect, but is largely determined through its adaptation processes to the environment to which it is exposed. These discussions indicate that the manifold of attachment mechanisms of insects was brought about through the long passage of evolution and adaption. In line with this way of thinking, a systematic classification of relations between the structure and mechanism required to actuate a function could pave the way into the material design just to the purpose. Learning the evolutionary struggles between plants and insects, as described in the previous section, is expected to open the way for a broad spectrum of material designs.

[NOTE 6] MPI:Max Planck Institute
[NOTE 7] CAESAR:Center of Advanced European Studies And Research
[NOTE 8] CILIA:Customized Intelligent Life-Inspired Arrays

4-2 Point 2: Compilation of Biological Resources into a Database is the Key

Compilation of a database that contains information regarding the structure-function correlations of living things from the viewpoint of taxonomy would provide a guideline to the biomimetic material designs capable of coping with a variety of applications. In other word, an effective utilization of the diverse bio-inventory is the key to bring diversity into material research. As evidenced by the effort of Professor A. Parker et al at London's Natural History Museum (i.e., "Compilation of database to provide a guideline in photonics materials design"), systematic accumulation of structure-function correlations in natural history is a very important contribution and the accomplishment should be made available to the researchers. Professor S. Gorb also noted in the preface to his book Attachment Devices of Insect Cuticle, "the fact that the observation of surface structure of living things became widely available owing to SEM (Scanning Electron Microscopy) was the driving force for the dramatic development in this field." The research organization that undertakes systematic and comprehensive observation of the surfaces of living things on the microscopic level will surely play an important role in the future biomimetics research. In the United States, compilations of databases such as "Nature's 100 Best" and "Biomimicry Taxonomy" are being contemplated.

4-3 Point 3: Win-win Collaboration among Biology, Natural History, and Material Science Is Essential

Gathering knowledge on nano- /micro-structures of living things and the underlying relations of how these structures lead to a manifestation of a function is one of the major research challenges for biology, especially for morphology and embryology. As exemplified in the success stories in European biomimetics research, an important thing for material science is to verify and recreate the working principle of the findings in biology, and yet another important thing is to feed back the results to biology. The bridging of fundamental and applied sciences and the collaboration among dissimilar disciplines shed new light on biological specimens (natural historical resource) and bestowed them with engineering values. This approach also enables the feedback of engineering knowledge to help elucidate the biological mechanism leading to the manifestation of functions. This is a win-win relationship brought about by collaboration among dissimilar disciplines, and the key aspects to achieve this are for a biologist to have sophistication that does not alienate him from mathematical sciences, and for a material scientist to have a lively curiosity about biology.

4-4 Point 4: Design of Energy-saving Materials Should Learn from the Multifunctionality and Environmental Adaptability of Living Things

The new generation biomimetic materials are characterized by their hierarchical structures that range in scale from nanometer to micrometers, and mimicking the mechanisms inherent to living things to actualize the desired functions. These hierarchical structures can exhibit water-repellent property in one aspect and anti-reflective property in another. Professor Barthlott et al refer to the multifunctionality of the surface of living things having such a hierarchical structure.[35]

For example, the moth-eye structure is found not only on a moth but also on many other insects. The water-repellent complex eye is considered to save the smaller insects, such as a mosquito, from drowning in falling raindrops. The wing surface of the Morpho is covered by scales with a hierarchical structure that gives rise to characteristic structure color, and the structure also endows the insect with water-repellent property. Professor Lei Jiang et al at the Chinese Academy of Science found that the wing shows repellency in the directions from the center of the wing to the outer edge, and adsorptive property in the reverse directions. The direction that the wing repels water drops coincides with the airflow created when the butterfly flutters its wings, indicating that the directional property may endow it with a self-cleaning function: the attached water drops are driven from the center to the outer edge, eliminating surface fouling.

The water-repellent property of surface nano- and microstructures is also found in the transparent wings of a cicada. Transparent wings make them hard to distinguish from the surroundings. The chestnut tiger butterfly (Parantica sita), known to make a long-distance journey, has partially transparent wings. On the other hand, Parnassius glacialis, although it is not a long-distance flyer, also has transparent wings. Detailed comparison of the wing surface microstructures of these two butterflies revealed that the transparent portion of a chestnut tiger butterfly's wing has an ordered array, although low in density, of scales exhibiting high levels of water repellency, and Parnassius glacialis does not have such an ordered array of scales, resulting in weak water-repellency. The diversity in the forms of water-repellency and optical properties manifestation is considered to be the result of evolution and adaptation processes.[36]

Recently, a proposal was made to utilize the multifunctionality of biomimetic surface structures (water-repellency, self-cleaning, anti-reflection, transparency, etc.) to solar cells. In the background of the variety of functions contained on the surface of living things may lie a hidden "energy-saving" design principle. A thorough review of the structures, functions, and behaviors of living things, from a viewpoint of environmental adaptability and energy conservation, will be necessary when an attempt is made to design a new material.

4-5 Point 5: Collaboration between Material and Mechanical Disciplines Is Highly Desirable

Collaboration between material- and mechanical biomimetics is also an important aspect. Current alienation of these areas seems to have been exerting a disadvantageous effect. In the research on sharkskin riblets, collaboration with microbiologists constituted an essential aspect from the viewpoint of anti-fouling, and collaboration with fluid dynamics researchers was also an integral aspect in view of friction reduction.

Water drop manipulation using a water-repellent material also presents research themes applicable to a variety of areas including MEMS and combinatorial chemistry. Especially in the research area of lab-on-a-chip, the newly emerging digital microfluidics technology requires the technique and devices that enable water drop manipulation. The phenomena called electrowetting-on-dielectric (EWD) is mainly used for water drop manipulation. EWD makes use of the finding that the contact angle of a water drop placed on a hydrophobic substrate decreases upon application of an electric field. The ant cow (aphid), cohabitant with ants, knows how to handle a water drop in masterly poise; this may provide a useful hint for a biomimetics device design. The ant cow (aphid) secretes a stable liquid drop (called a liquid marble), thus preventing itself from drowning in the liquid inside the nest.[37] On the other hand, research that uses a non-EWD method for liquid drop manipulation has been underway. Observation of the phalarope revealed that the bird could move water upward to its mouth, defying gravity, using the open-close movement of its bill and surface tension of water. This finding indicates a potential application to reduce the resistance of the flow of liquid inside a pipe.[38] The development of MEMS chips that bases a flow passage on a new operational principle is expected. A type of beetle in Namib Desert is known to collect water from mist drops. In contrast, some types of cockroaches in the desert are believed to be able to adsorb water drops around their mouths even in humid conditions below saturation vapor.[39] These findings may provide useful hints for device designs that enable water drop manipulation in condensation/evaporation processes without consuming energy.

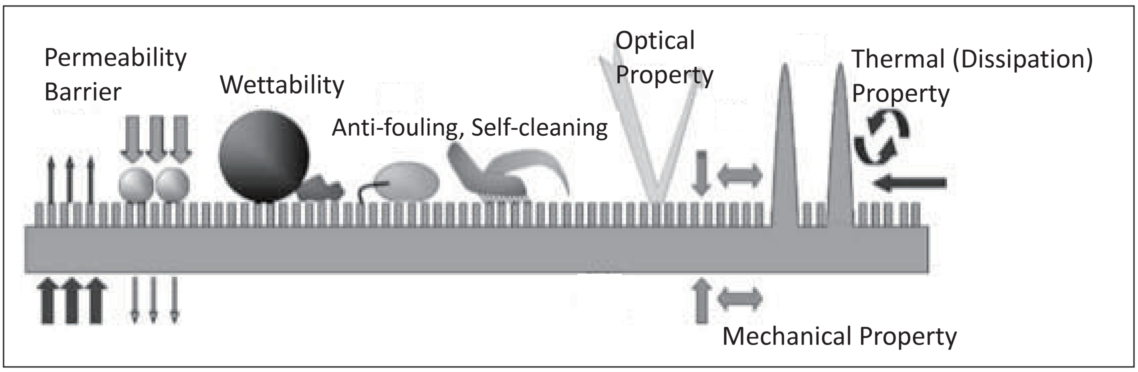

Figure 8 : Multifunctionality of Biological Surfaces

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4-6 Point 6: Formation of Self-organized Hierarchical Structure in Living Things Presents Valuable Clues for the Innovation of Manufacturing Technology

The new generation biomimetics research has a potential for bringing about an innovation in manufacturing technologies. Professor J. Vincent at Bath University, a biologist and one of the leaders in British biomimetics research, used a problem-solving method called TRIZ to conduct a comparative analysis of the elements of which a biological entity is composed and those used in an artificially constructed entity by means of industrial techniques. He concluded that, while living things make efficient use of "information," "space," and "structure" for their structure formation, the structure formation by means of conventional industrial techniques depends largely on "energy" and "materials."[40] Living things create information containing molecules such as DNA and proteins from very common elements such as carbon, oxygen, and nitrogen; these molecules in turn form structures such as a membrane and organelle, and the structural development proceeds further into a hierarchical formation of cells, tissues, and organs. On the other hand, industrial products such as the high-speed electric circuit use rare elements such as gallium and arsenic, and hack the raw materials into pieces using such technology as lithography accompanied by the consumption of enormous amounts of energy.

The structure formation processes in living things consists of a complex combination of chemical reactions governed by the program inscribed in the genes, where the self-assembly of molecules and self-organization of these molecular assemblies function quite effectively. The living things create their peculiar structures and bring a manifold of functions to life using neither the lithography nor petroleum. Professor Vincent's analysis suggests the possibility of new production technologies with a lesser degree of dependence on energy and materials.

In many cases of the development of new generation biomimetic materials, the "initial model" is manufactured using some of the nanotechnologies (e.g., electron beam drawing, lithography) for principle verification. In subsequent stages where the move to commercialization is in view, methods for efficient and economic production are required. A search for production technologies inspired by living things is needed, where the variety of techniques used in nanotechnology must be reviewed from a comprehensive point of view.[41] These include molding technology (e.g., nanoimprinting), patterning technology (e.g., ink-jet printing), crystal growth technology, application of self-assembly phenomena (e.g., block copolymer lithography, micro contact printing), and application of self-organization phenomena (e.g., dissipative structures). It seems unlikely that chemical reaction processes alone produce structured materials, but future incorporation of physical processes such as self-assembly and self-organization has the potential to produce highly structured materials.

Putting together the discussions so far, we can conclude that biomimetics has a potential to bring about a paradigm shift in industrial technologies. In conventional industrial technology, a superhydrophobic surface is obtained through the use of fluorine coating. The lotus leaves, in contrast, use organic material (wax-like secretion) and micro/nanostructure to realize a superhydrophobic surface. We use compound semiconductors to produce a highly sensitive infrared sensor, and a jewel beetle detects a fire from far away by using volume expansion of a liquid. Living things have realized equal or superior functionalities to man-made equivalents using completely different mechanisms. As Professor Vincent indicated, living things are able to create nano/microstructure without resorting to lithography. It is apparent that the living things possess a scheme of production techniques and system design that are quite different from the ones that we have cultivated since the industrial revolution. The new trend of biomimetics research involves a paradigm shift in modeling and fabrication techniques of materials and system designs. This new line of thinking seems to have already established its place in Europe and the United States as a policy concern toward the realization of sustainable society where such issues as the environment, energy, and natural resources must be addressed.

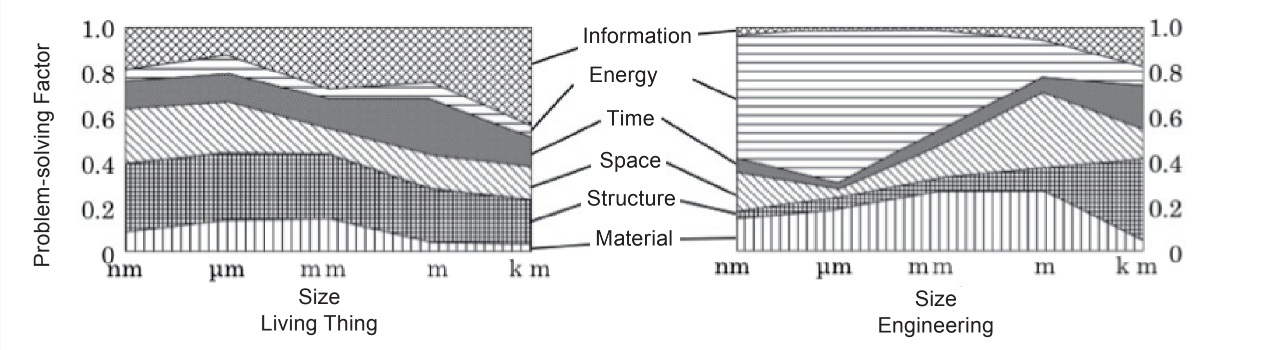

Figure 9 : Comparison of Manufacturing Method: Living Thing vs. Engineering (Analysis by BioTRIZ)

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5 The Approaches Employed in Advanced Countries

5-1 United Kingdom: Perception and Approach

In January 2007, the then Department of Trade and Industry (DTI) of the U.K. compiled a report called "Biomimetics: strategies for product design inspired by nature. A mission to the Netherlands and Germany." This report, compiled by DTI Global Watch Mission, described the potential contributions of biomimetics to the industrial arena in the U.K. According to the report, biomimetic research is being actively taken up in the U.K., Germany, the Netherlands, and the United States; among these countries, Germany is one step ahead of others in systematic integration of basic research and industrial applications. In the Netherlands, several advanced research organizations and enterprises have applied the biomimetics concept to product developments and designs, but as the report pointed out, they lack collaborative links among these individual research and development groups.

A network called "BIONIS",[NOTE 9] established in the U.K. in 2002, with core members consisting of the enterprises and universities in the U.K., issues newsletters transmitting topics in biomimetics and conference information internationally. Well-established links have been in place in the U.K. between fundamental research and prototyping, but it seems that the passage toward commercialization has not yet been well implemented. In the same light, in a report focused on "Multifunctional Materials" compiled by DTI's Material Innovation & Growth Team in 2006, the biomimetic material was taken up as one of the areas of future importance for the U.K., in addition to composite materials, coating materials, and nanostructure materials.

5-2 Germany

As mentioned above, Germany is acclaimed by the U.K. to have well-established research networks, and its new generation biomimetic research is characterized by a clear emphasis on biology. The "National Strategy on Biological Diversity" (2007) carried out under the initiative of the German government includes a section titled "Biological diversity and its innovation potential"; and it introduced such accomplishments as the lotus effect, gecko tape, and the jewel beetle's infrared sensor as potential technical innovation enablers. In COP9 (The 9th meeting of the Conference of the Parties of Convention on Biological Diversity) held in Bonn in 2008, the government of the Federal Republic of Germany initiated "Biodiversity in Good Company" and called for private enterprises to get involved in the activities of the biodiversity convention, as it has a significant impact on business activities, including the procurement of raw materials and manufacturing procedures.

In Germany, BIOKON[NOTE 10] has shown a good track record in market development, organization, and transfer of knowledge. BIOKON is the network established in 2001 under the auspices of, and funded by the Federal Government of Germany for industry-academic-government collaboration among 28 research organizations. BIOKON is characterized by its embedded design to enable organization of three important links in biomimetics: biology-engineering collaboration, collaboration among dissimilar engineering fields, and business-academia collaboration. Since 2009, the network has transformed itself into "BIOKON International," funded by the monetary support of more than three million euro from the Ministry of Education and Research of Germany, aiming to become an international network in the future. Among the eight board members, four come from France, Sweden, the Netherlands, and the U.K. With an aim of becoming independent from the government starting in 2012, it will host, as mentioned at the beginning of this article, the world's first "International Industrial Convention on Biomimetics" in 2011. As just described, the German government is proactively promoting biomimetics, eliminating vertically divided administrative functions, and the Federal Ministry of Economics and Technology devoted a significant portion of its white paper to this subject.[42]

5-3 Other European Countries

In FP7, the European Union has been pushing along biomimetics-related programs in many fields such as information and telecommunication, energy, and medicine,[43] as well as anti-fouling.[11] The white paper of the GENNESYS[NOTE 11] Initiative (Grand European Initiative on Nanoscience and Nanotechnology using Neutron-and Synchrotron Radiation Sources) devoted a significant portion of chapter three to Biomimetic nanomaterials. In Austria, the Federal Ministry for Transport, Innovation and Technology has been gearing up for the formation of academia-business enterprise networks in such a variety of fields as machinery, material, and biology.[44] In Sweden, a financing company (Swedish Biomimetics 3000®) specially designed to support commercialization efforts of biomimetics research has been established.[45]

5-4 United States

The white paper of the National Academy (U.S.), as mentioned at the beginning of this article, stated that, as one of the proposals relating to "Next Generation Bioinspired Materials," it is a challenge for scientific understanding "to select a wide range of biological multi-functional systems that provide an inspiration for the design of advanced materials." J. Benyus, the advocator of Biomimicry, established an incorporated nonprofit organization ("Biomimicry Institute") and a consulting firm ("Biomimicry Guild"), and opened a freely accessible database called "Biomimicry Taxonomy" at the website "Ask Nature", providing a list of tips useful for application of biodiversity to a variety of areas in science and technology. He also hosts the "Biomimicry and Design Workshop" regularly to transmit relevant information.

[NOTE 9] BIONIS: The Biomimetics Network for Industrial Sustainability
[NOTE 10] BIOKON: Bionics Competence Network
[NOTE 11] GENNESYS: Grand European Initiative on Nanoscience and Nanotechnology

6 The Approaches Employed in Japan: Challenges and Proposals

6-1 The Approaches Employed in Japan

As shown in Table 1, books and journals have been published in Japan relating to nature technology and biomimetics since the turn of the century, and surveys have been carried out (mainly by the Ministry of Economy, Trade and Industry) on establishing biomimetics policies. The Ministry of Education, Culture, Sports, Science and Technology adopted, in its "21st Century Center of Excellence (21st Century COE)" project, several related subjects as major graduate education programs, including biomimetic manufacturing (engineering) and novel applications of biological resources (agriculture). Several international conferences on these areas have been held under the initiative of Japanese researchers. Several technologies (e.g., water-repellent materials/paints, optical films with moth-eye structure) have already been put into practical use in Japan, and the biomimetic technology has been progressively attracting interest from business enterprises that are searching for new material designs and innovative manufacturing techniques.

6-2 Japan-Europe Comparison in New Generation Biomimetics Research and Development

The new trend in biomimetics is highly expected to go global, since they have the potential to sprout new technological innovations promoting new systems of science and technology that are capable of addressing the problems of modern society (i.e., energy, environment, and resource). As evidenced by the success stories in Europe and the United States introduced in this article, the collaboration between dissimilar fields in engineering and biology is integral to achieving such objectives. In the backdrops of highly active and original biomimetics research and development in Europe and the United States, a cultural factor that precludes vertical segmentation of science and technology seems to be taking effect. To further promote collaborations among dissimilar areas, the German government is practicing administrative

Table 1 : Surveys, Research Projects, and Books Related to Biomimetics in Japan

Survey	The survey conducted by the Tohoku Bureau of Economy, Trade and Industry "Survey on Industrial Pollution Prevention Technologies and Their Business Feasibility: In Relation to Nature Technologies" "Survey on Monozukuri Technologies That Mimic Biofunctions," NEDO, 2007 "Survey on the Next Generation Biomimetic Materials," NEDO, 2009
Research Project	"Creation of Nature-Guided Materials Processing," Nagoya University 21st Century COE Program, 2002 "Innovative Food and Environmental Studies pioneered by Entomomimetic Sciences," Kyoto University 21st Century COE Program, 2004
Concerns in Business Sector	Aid funds for "Monozukuri Forum Inspired by Nature," "Aid for Monozukuri Researches Inspired by Nature," Sekisui Chemical Co., Ltd. "Challenge to 2030: Next Generation Industrial Technologies" Bio-mimicry, Parts 1 and 2, Nikkei Sangyo Shinbun, February 9–10, 2010 "Technology Watch," Environment Friendly Technologies Inspired by Nature, NIKKEI, January 23, 2010 "Biodiversity for Company Management," Parts 1, 2, and 3, NIKKEI, May 4–5, 7, 2010 "Pictorial Presentation: Japanese Economy 2010," Amazingly Efficient Monozukuri Inspired by Living Things, Economist Special Issue
International Conference	International Conference on "Biomimetics Material Processing," 2001–2009 International Symposium on "Engineering Neo-Biomimetics," 2009
Learned Book	"Biomimetics Handbook," 2000; "New Development of Biomimetics," 2002; "'Fiber': Super Biomimetics," 2006; "Plantmimetics," 2006; "New Generation Nanomaterials Inspired by Insects," 2008; "Insect Mimetics," 2008; "Future Created by Insectology," 2009
Introductory Book	"Snail Teaches Us: Ultimate Monozukuri Inspired by Nature," 2004; "Monozukuri Inspired by Nature," 2005; "Power of Insects," 2006; "Sophisticated Technology Inspired by Nature," 2009; "The Earth Teaches Us: Miraculous Technology," 2010

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Table 2 : Japan-Europe Comparison in the Next Generation Biomimetics Research
(○ : Good, △ : Needs improvements, × : Insufficient)

	Europe	Japan
Linkage among Material Science, Biology, and Natural History	○ Variety of good linkages under the initiative of biologists; Nanotechnology is integral Collaboration required for budget allocation	× Linkage is only seen between molecular-level biology and material science.
Intra-Engineering Linkage (material and mechanics)	○ Concentrated budget allocation on collaborative projects involving dissimilar areas	× Next to no linkage between material and mechanics/robotics domain
Academia-Industry Alliance	△ German government actively supports alliance. Quickest way is to establish a venture. Large U.K. enterprises tend to keep a "wait and see" position.	△ Catch-up effort to European accomplishment depends largely on private sector.
Educational Program	○ Collaborations in doctoral programs among plural of universities (Germany). Variety of areas are involved.	△ Improvement effort such as 21COE. Programs are contained in single area/university.
Museum Involvement	○ Database compilation of inventories (specimen collection)	× Lack of contact with engineering (material science and mechanics)
Network Formation (academia-industry, between dissimilar areas)	○ Active network formation (especially in Germany and the U.K.); German government supports proactively (e.g., European Consortium)	× Nil
Budget	○ In addition to national budget, EU sets priority subject in FP6, FP7.	× General external funding
Policy Involvement	○ Each government conducts independent survey. Compilation of white papers in various academic domains and proactive policy proposals.	△ Surveys are conducted mainly by METI and NEDO. Survey almost limited to near-industrialization subjects. Next to no contribution from biologists.

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guidelines that favor, in terms of funding, only the researches involving joint efforts among dissimilar fields. If we try to extract the challenges Japan must face in the new generation biomimetics research, comparison with the situation in Europe could provide meaningful findings.

Table 2 summarizes the comparison results between Japan and Europe in terms of collaborations among dissimilar fields, university-industry relations, educational programs, budget allocation, and policy-making surveys. In Europe, the problems presented from biology have been proactively addressed in collaboration with other scientific fields (e.g., nanotechnology), and, as can bee seen from the table, human resource cultivation and network formation have been pushed forward as elements of policy framework involving even such entities as museums, as well as various industrial sectors. Unfortunately, in contrast to the situation in Europe, collaborative efforts across dissimilar fields have not been promoted enough in favor of the projects that fit in the vertically segmented system. Admitting that Japan is not very good at forging a collaboration among dissimilar fields and creating a fusion area, it seems apparent that any effort done by one single sector in Japan to catch up and follow up on the successes of biomimetics researches in Europe and the United States will not dissolve Japan's current lagging position.

6-3 Problems in Japan and Their Background

The reasons for the new generation biomimetics research—an accomplishment of collaborative effort between dissimilar fields (i.e., biology and nanotechnology)—have continuously been rough going in Japan. Japan has had a tradition and accomplishments in Biomimetic Chemistry, which can be considered to be molecular biomimetics, a part of it giving birth to a trend of biomaterial research. This trend has grown up to now in the area of medical applications, leading to successful collaboration between material science and medicine. Behind the successful medicine-engineering collaboration in Japan lies the fact that biomaterial researchers had a working knowledge of medicine and they also had a good understanding of the challenges and issues at the medical front. A substantial academic society and educational system also contributed to these successes. On the other hand, in supramolecule science, which is considered to be the natural successor to molecular biomimetic researches and is the central research area for raising the level of nanotechnology addressing atoms, molecules, and molecular assemblies, there has been difficulty in finding suitable research areas to collaborate with (i.e., limited to areas where similar size of objects are handled). The research area that handles the size range from nanometers to micrometers, and even to millimeters—the territory of taxonomy and morphology that triggered the rise of the next generation biomimetics in Europe—was not the area of specialty of the supramolecule science in Japan. As a result, hardly any attempt was made to collaborate with such dissimilar areas as entomology, zoology, and botany. This situation caused the material biomimetics research in Japan to start by importing biomimetic designs of new materials from the papers published in Europe and the United States. In such a stage, neither the knowledge of botanists nor collaboration with them is required. The problem on the side of material science lies in the fact that researchers did not find merit in searching for clues for a new material design from structures and functions of living things through contact with biologists alone. They resigned themselves to catching up with the ideas found in Europe and the United States. The origin of this problem can be traced back to the lack of biological knowledge on the side of Japanese material scientists, and they were reluctant to engage in people-to-people exchanges. In marked contrast to this, the biomaterial researchers were eager to acquire medical knowledge. They proactively organized academic societies and cultivated human resources, resulting in a fruitful medicine-engineering collaboration.

On the side of biology, the origins of the problems can be sought in the extremely vertically compartmentalized learning system and academic organizations. Segmentation of a learning system is much more far-reaching in biology than in engineering disciplines. Taking insect research as an example, there are a variety of approaches, depending on their standpoints, including taxonomy, agronomics (anti-bug point of view), physiology, and developmental biology: intercommunion among these researchers is not necessarily frequent. In the area of biomimetics, the main task assigned to biology is to elucidate the nano/micro structures of living things and their biological functions. In Europe, taxonomists and morphologists have played leading roles in the next generation biomimetics research. In Japan, in stark contrast to Europe, no biomimetics-related research has been reported in the fields of taxonomy, morphology, and embryology. Agricultural entomology has developed as an applied science, as its main research objectives have been the silkworm and its destructive insects. As a theme in the 21st Century COE (see Table 1), the Agricultural Department of Kyoto University put forward the concept of "entomomimetics" as an aspect of "Insect-inspired science." In line with this concept, attempts have been made to develop inset robots in collaboration with mechanical biomimetics. As Professor Kenji Fujizaki, the representative of the group, started an exchange with Professor S. Gorb at Kiel University, the leader in next generation biomimetics research in Germany, the interest on material biomimetics has been spreading among the applied entomology community.

"Insect Mimetics" published in 2008 is the first full-fledged handbook on this subject in Japan and was compiled mainly through the efforts of animal physiologists, wherein many researches carried out by European entomologists and animal physiologists (including Professor J. Vincent's accomplishments) are introduced. The chief editor Tateo Shimozawa (Professor Emeritus, Hokkaido University) is a physiologist with a background in electronic engineering, and his research on insect's sensory hairs, which introduced an engineering method in this area, was highly acclaimed in Europe and the United States. The results of his research are also known to help launch the project of Professor J. Casas et al (see the description in section 3-8). Although lagged behind Europe and the United States, the concept of biomimicry seemed to have germinated among the biologists who can consider the subject in view of engineering and agricultural applications. However, the "entomomimetics" in the agronomics community and the "insect mimetics" in physiology community are—in spite of the fact that they share challenges and awareness of the problems involved, and similar contacts with material science and mechanical engineering—undergoing development largely independent of each other and under the influence of the vertically compartmentalized academic system and scientific communities. As a result, in spite of the fact that the Japanese scientific community had the basis and potential to develop the next generation biomimetics research under biologists' initiative, these systematic and conventional problems presumably hindered it from developing into the new trend that is being seen in the European arena.

6-4 Challenges and Proposals

To construct a new technology system in Japan, which may be called "biomimetic engineering," characterized by the adoption of a "material and system design inspired by biofunctions" and "manufacturing technology inspired by bioprocesses," many issues must be addressed, including: (a) collaboration between engineering (material science, mechanical engineering, etc.) and natural science (biology, natural history); (b) collaboration among dissimilar areas inside biology and engineering, (c) a rapid establishment of academia-industrial alliance, and to promote these measures, (d) a system for human resource cultivation and education in view of reducing barriers separating the dissimilar disciplines. For rapid promotion and activation of collaboration among dissimilar areas, the establishment of a center facility that functions as the "biomimetic initiative" (the possible title may be "the biomimetic center for cross-governmental collaboration") may prove effective. This facility should organize comprehensive collaborative research entities cutting across the national agencies (National Institute for Materials Science, National Institute of Advanced Industrial Science and Technology, National Institute of Agrobiological Sciences, RIKEN, National Institute for Environmental Studies, National Museum of Nature and Science, etc.), the natural history museums managed by local authorities, universities, and other relevant facilities. It should also propose, as policy challenges, the launch of academic-industrial alliance projects and collaborative research programs that fuses dissimilar academic disciplines. Furthermore, the following activities should be promoted concurrently: human resource cultivation programs involving multiple academic societies in different academic domains, scientific education programs and scientific enlightenment activities as a joint effort among science museums, universities and academic societies, and recurrent education for technologists.

6-4-1 Roles of Museums

The role of museums, with a vast amount of biological specimen, or biological resources information, is essential. It is an urgent task to create a comprehensive biomimetic database through consolidation and organization of the museums' inventories, whereby such approaches as data mining and "knowledge structuring" should be utilized. The database enables researchers to find engineering values in the collected specimen, which is useful for both taxonomy and morphology from an academic point of view as well. In fact, the museums in Europe are actively practicing cooperative activities and academic-industrial collaborations with material/device researchers based on database information (e.g., electron micrographs). The procedure of compiling a database from biological resources inventory from an engineering viewpoint provides a platform for engineers and biologists to know each other. This is exactly the process of transforming a "specimen" into a "treasure," from which the researchers could find an objective of cooperative research. Diversity of living things is reflected in the diversity of new materials, because the latter is designed based on the concept obtained by mimicking the former.

6-4-2 Creation of New Academic Research Domain through Collaboration of Dissimilar Areas

Living things form hierarchical structures (from nano-, to micro-, and even to macro-scale) autonomously. The objective of the new generation biomimetics research is to elucidate the structures (the scale of which ranges from nanometers to micrometers) and their functions, as well as the mechanisms through which the structure manifests its function. This is a different approach from that employed by molecular biology; and even nanotechnology did not use the approach in the process of its development. The biomimetics research is exactly the deed of filling the gap between the nano- and micro-domain, and the linkage between molecular nanotechnology and microstructure of living things will lead to a fusion of life science and engineering. In turn, the accomplishments of biomimetics research will be fed back to development biology and morphology. This is the essence of the new generation biomimetics research that makes it worthwhile to be ranked as a new academic domain.

6-4-3 Creation of Academic-Industrial Alliance Projects for Practical Realization

The discovery of the lotus effect is a success story that symbolizes biomimetics research and development in Germany, and the German government is helping form an academic-industrial alliance network (BIKON) as a policy concern. This also indicates that, even in Europe, promotion of academic-industrial alliance in this field needs assistance from the government. Although the situation in Japan is one lap behind, a political leverage for such network formation could have an enough potential to work miracles.

In addition to promoting academic collaboration between biology and engineering, an academic-industrial collaboration should be organized into a joint-research consortium under a political initiative involving the group of companies that can address energy, environment, and resource issues, and the challenges and projects for the academia-business collaboration entity should be set. For example, incorporation of the moth-eye structure into solar cells facilitates more efficient energy production; application of low-friction materials inspired by the insect's legs to automobiles helps achieve higher efficiency in energy usage; and the development of bottom-up nanotechnology based on self-assembly and self-organization toward its technologising will realize manufacturing processes that consume much less energy. These challenges, at once, represent greater political challenges to be overcome toward the realization of a sustainable society.

6-4-4 Education and Human Resource Cultivation

The cultivation of engineering researchers with an interest and understanding in biology is integral to the future development of biomimetics research. As was described in 3-6, Germany has a COE program (called BIONIC Graduate) targeted at doctoral course education. This program works in conjunction with the consortium for the technologies mimicking the sensory hair of insects, and the researchers who specialize in different areas of expertise, from different universities, carry out cross-border training to graduate students. An incorporation of biology into engineering education is essential for the students to find engineering values in the structures and functions of living things. Through biomimetics research, it is also important to enhance science education in elementary and middle schools and recurrent education of corporate researchers, where the enlightenment and publicity capability of museums will play an essential role.

Behind the reasons that caused Japan to fail to join the trend toward new generation biomimetics research seems to lie the educational and cultural background of this country: the current educational system is producing biologists who have an aversion to physics and mathematics, engineers who dislike memorizing, and students who enter medical departments without having learned biology in high school. Department organization in universities is still subject to the influence of a vertically compartmentalized educational system that started in Meiji-Restoration, and this has an effect on elementary and middle school education, and especially on science education. In addition, a highly homogeneous organization of academic societies may be an element to producing a passive culture toward alliance among dissimilar areas. To try to free Japan from catching up with Europe and the United States, and to demodernize toward an advanced scientific and technological powerhouse, it is important to cultivate human resources who have the capacity to "set a problem to produce a challenge."[46] Especially, toxonomists with an understanding of physics, and engineers who are familiar with insects are required in future.

Acknowledgement

Through the writing of this article, the following researchers offered helpful discussions and guidance. The author extends sincere thanks to: Mr. Masanori Tomokuni (manager of the Zoological department, National Museum of Nature and Science), Professor Kenji Hujizaki (Agronomical department, Kyoto University), Mr. Tateo Shimozawa (Professor Emeritus, Hokkaido University), Mr. Hisashi Horishige (section manager, Historical Museum of Hokkaido), Professor Takahiko Hariyama (Hamamatsu University School of Medicine), and Professor Jun Takahara (Institute of Materials Chemistry and Engineering, Kyushu University).

References

[1] http://www.otto-schmitt.org/

[2] "Clusters of Excellence" is an example of a large-scale project (under the initiative of the German government) preconditioned to be a collaboration among dissimilar areas.
http://www.dfg.de/en/research_funding/programmes/excellence_initiative/clusters_excellence/index.html

[3] For example: K. Tsujii "Superhydrophobicity and superhydrophilicity: mechanism and application." Yoneda Publishing, 2009.

[4] W. Barthlott, "Scanning electron microscopy of the epidermal surface in plants.," Scanning Electron Microscopy in Taxonomy and Functional Morphology (Systematics Association Special Volume No. 41), ed. D. Claugher. Clarendon Press, Oxford, 69–94, Clarendon Press, Oxford, 1990. W. Barthlott, C. Neinhuis, "Purity of the sacred lotus, or escape from contamination in biological surfaces" Planta, 202(1), 1–8 (1997)

[5] L. Feng, Y. Zhang, J. Xi, Y. Zhu, N. Wang, F. Xia, L. Jiang, "Petal Effect: A Superhydrophobic State with High Adhesive Force," Langmuir, 24(8), 4114–4119. 2008.

[6] M. H. Jin, X. J. Feng, L. Feng, T. L. Sun, J. Zhai, T. J. Li, L. Jiang, "Superhydrophobic Aligned Polystyrene Nanotube Films with High Adhesive Force," Adv. Mater. 17(16), 1977–1981. 2005.

[7] A. R. Parker, C. R. Lawrence, "Water capture by a desert beetle," Nature 414(6859), 33–34. 2001.

[8] L. Zhai, M.C. Berg, F.C. Cebeci, Y. Kim, J.M. Milwid, M.F. Rubner, R.E. Cohen, "Patterned Superhydrophobic Surfaces: Toward a Synthetic Mimic of the Namib Desert Beetle," Nano Lett.,6(6), 1213–1217. 2006

[9] D. Ishii, H. Yabu, M. Shimomura,"Novel Biomimetic Surface Based on a Self-Organized Metal-Polymer Hybrid Structure," Chem. Mater., 21(9), 1799–1801. 2009.

[10] F. Xia, L. Jiang, "Bio-Inspired, Smart, Multiscale Interfacial Materials," Adv. Mater., 20(15), 2842–2858. 2008.

[11] http://www.biosciences.bham.ac.uk/SEACOAT/index.htm

[12] T. Hariyama,"Structural Colors in Fish," Structural Colors in Biological Systems –Principles and Applications– (edited by S. Kinoshita and S. Yoshioka), Chapt. 5. Osaka University Press, 2005.

[13] A.L. Ingram and A.R. Parker, "A review of the diversity and evolution of photonic structures in butterflies, incorporating the work of John Huxley (The Natural History Museum, London from 1961 to 1990)," Philos. Trans. R. Soc. London, Ser. B, 363(1502), 2465–2480. 2008.

[14] K. Autumn, M. Sitti, Y.A. Liang, A. Peattie, W. Hansen, S. Sponberg, T. Kenny, R. Fearing, J. Israelachvili, and R.J. Full, "Evidence for van der Waals adhesion in gecko setae" PNAS, 99(19), 12252–12256(2002), W. Kenny, Ronald Fearing and Robert J. Full, "Adhesive force of a single gecko foot-hair," Nature, 405(6787), 681—685. 2000.

[15] M. Sitti, R.S. Fearing,"Synthetic gecko foot-hair micro/nano-structures as dry adhesives," J. Adhesion Sci. Technol., 17(8), 1055–1073. 2003.

[16] A.K. Geim, S.V. Dubonos, I.V. Grigorieva, K.S. Novoselov, A.A. Zhukov, SYU. Shapoval, "Microfabricated adhesive mimicking gecko foot-hair," Nature Materials, 2(7), 461–463. 2003.

[17] J. Lee, B. Bush, R. Maboudian and R.S. Fearing, "Gecko-Inspired Combined Lamellar and Nanofibrillar Array for Adhesion on Nonplanar Surface," Langmuir, 25(21), 12449–12453. 2009.

[18] http://bdml.stanford.edu/twiki/bin/view/Rise/StickyBot
Also developed by BAE Systems (an U.K. armament industry company),
http://www.bae-systemsmarine.com/fias2006/news/news197.htm

[19] C.G. Bernhard, William H. Miller, "A corneal nipple pattern in insect compound eyes," Acta Physiol Scand., 56(3–4), 385-386. 1962. W.H. Miller, G.D. Bernard, and J.L. Allen, "The Optics of Insect Compound Eyes," Science, 162(3855), 760–767. 1968.

[20] S.J. Wilson, M.C. Hutley, "The Optical Properties of 'Moth Eye' Antireflection Surfaces," J. Mod. Opt., 29(7), 993–1009 (17). 1982.

[21] J. Zhao, A. Wang, P. Campbell and M.A. Green, "19.8% Efficient Honeycomb Multicrystalline Silicon Solar Cell with Improved Light Trapping," IEEE Transactions on Electron Devices, 46(10), 1978–1983. 1999.

[22] W. Baumgartner, F. Fidler, A. Weth, M. Habbecke, P. Jakob, C. Butenweg, W. Bohme, "Investigating the Locomotion of the Sandfish in Desert Sand Using NMR-Imaging," PLoS One., 3(10), e3309. 2008.

[23] R.A. Berthe, G. Westhoff, H. Bleckmann, S.N. Gorb, "Surface structure and frictional properties of the skin of the Amazon tree boa Corallus hortulanus (Squamata, Boidae)," Journal of Comparative Physiology A, 195(3), 311–318. 2009.

[24] http://www.bionikgraduate.uni-bonn.de/index.php

[25] M. Varenberg , S.N. Gorb, "Hexagonal Surface Micropattern for Dry and Wet Friction," Adv. Mater., 21(4), 483–486. 2009.

[26] E. Gorb, and S. Gorb "Functional surfaces in the pitcher of the carnivorous plant Nepenthes alata: A cryo-SEM approach.," Functional Surfaces in Biology: Adhesion Related Phenomena. Volume 2. (Gorb, S., ed.), Springer, Dordrecht, Heidelberg, London, New York, 205–238. 2009.

[27] T. Onda, S. Shibuichi, N. Satoh and K. Tsujii, "Super-Water-Repellent Fractal Surfaces," Langmuir, 12(9), 2125–2127. 1996.

[28] D. Voigt and S. Gorb, "An insect trap as habitat: cohesion-failure mechanism prevents adhesion of Pameridea roridulae bugs to the sticky surface of the plant Roridula gorgonias," J. Exp. Biol., 211(16), 2647–2657. 2008.

[29] H. Schmitz, M. Murtz and H. Bleckmann "Infrared detection in a beetle," Nature, 386(6627), 773–774. 1997.

[30] T. Shimozawa and M. Kanou, "Varieties of filiform hairs: range fractionation by sensory afferents and cercal interneurons of a cricket," J.Comp.Physiol., 155(4), 485–493. 1984. T. Shimozawa and M. Kanou, "The aerodynamics and sensory physiology of range fractionation in the cercal filiform sensilla of the cricket Gryllus bimaculatus." J.Comp. Physiol., 155(4), 495–505. 1984.

[31] T. Shimozawa, J. Murakami and T. Kumagai: F.G. Barth, J.A.C. Humphrey and T.W. Secomb (eds.), Sensors and Sensing in Biology and Engineering, 145–157, Springer-Verlag, 2003.

[32] G. J. M. Krijnen, T. S. J. Lammerink, R. J. Wiegerink, J. Casas"Cricket inspired flow-sensor arrays," IEEE Sensors, 28–31; 539–546. 2007.

[33] N. Mhatre, F.Z. Montealegre, R. Balakrishnan, D. Robert "Mechanical response of the typmanal membranes of the tree cricket Oceanthus henryi (Orthoptera: Gryllidae: Oecanthinae)," Journal of Comparative Physiology A, 195; 453–462. 2009.

[34] S. Gorb, "Functional Surfaces in Biology, Vol. 1 Little Structures With Big Effects, Volume 2 Adhesion Related Phenomena." Springer, 2009.

[35] K. Koch, B. Bhushan, W. Barthlott, "Multifunctional Surface Structures of Plants and Their Occurrence in Various Environments: An Inspiration for Biomimetics." Materials Science, 54; 137–178. 2009.

[36] P.P. Goodwyn, Y. Maezono, N. Hosoda and K. Fujisaki "Waterproof and translucent wings at the same time: Problems and solutions in butterflies." Naturwissenschaften, 96(7); 781–787. 2009.

[37] N. Pike1, D. Richard, W. Foster, L. Mahadevan "How aphids lose their marbles." Proc. R. Soc. Lond. B, 269(1497); 1211–1215. 2002.
[38] M. Prakash, D. Quere, J.W.M. Bush, "Surface Tension Transport of Prey by Feeding Shorebirds: The Capillary Ratchet," Science, 320; 931–934. 2008.
[39] M.J. O'Donnell, "Site of water vapor absorption in the desert cockroach, Arenivaga investigata" PNAS, 74(4), 1757–1760. 1977.
[40] J.F.V. Vincent, O.A. Bogatyreva, N.R. Bogatyrev, A. Bowyer, and A.K. Pahl, "Biomimetics: its practice and theory," J.R. Soc. Interface., 3(9): 471.482. 2006. http://www.biotriz.com/main.shtml
[41] S.J. Abbott, P.H. Gaskell "Mass production of bio-inspired structured surfaces Proceedings of the Institution of Mechanical Engineers," Part C: Journal of Mechanical Engineering Science, 221(10); 1181–1191. 2007.
[42] www.photonicnet.de/download/jahresbericht_kompetenznetze-de.pdf
[43] http://cordis.europa.eu/fp7/ict/fet-proactive/bioict_en.html#what, http://cordis.europa.eu/fetch?CALLER=FP7_PROJ_EN&ACTION=D&RCN=85749, http://nanoma.zenon.gr/, http://cordis.europa.eu/fp7/ict/micro-nanosystems/projects_en.html#Micro-Nano-Bio%20Convergence
[44] Following the publication of "Bionik und Verkehrstechnologie" (http://www.bmvit.gv.at/innovation/aktuell/downloadsaktuell/bionik_handout.pdf) from Australian Government in 2008, "BIONIK Innovation & Qualifikation" appeared in 2010.
[45] http://www.swedishbiomimetics.com/index.htm
[46] Akihiko Matsui: "The end of 'Westernization' and the Japanese Economy," Nikkei, March 28, 2010 (from the column "Keizai Rondan")

Profile

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5

Application of Graphene to High-Speed Transistors: Expectations and Challenges

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1 Introduction

1-1 Discovery of Graphene; Potentiality of Breaking through the Limitations of Semiconductors

As illustrated in Figure 1, the chemical structure of graphene is composed of hexagonal 6-membered carbon units repeating infinitely in two dimensions and forming a thin sheet. Carbon nanotubes (CNT) have a similar structure. Longitudinal unzipping of a CNT and rolling-out infinitely makes graphene.

Graphene is a single atomic layer exfoliation of graphite crystal. Graphene can be considered as the final compound at the end of the series of aromatic hydrocarbons which start from benzene, continue to naphthalene, and go far beyond. So, the structure of graphene has been well known, and there is nothing new to add. However, graphene is a two-dimensional material with a thickness of only one atom and was not isolated until recently.

In 2004, Geim[1] with his colleagues succeeded in isolating graphene flakes by a very simple method of repeated peeling-off, by scotch tape, of Highly Oriented Pyrolytic Graphite (HOPG). The report by Geim and the following reports have revealed that graphene exhibits tremendous electronic, electric, mechanical and chemical properties. Now, research works are spreading into various fields. The most important property among them is its extremely high electron mobility.[NOTE] Electron mobility is roughly an indicator of the speed of electrons in a solid. Therefore, using a material with high electron mobility implies the possibility to realize high-speed transistors. The reported electron mobility of the first isolated graphene was 10^4 cm^2/ V sec, which is almost one order of magnitude higher than 1350, the electron mobility of silicon or typical semiconductor material, and comparable to 8600, the mobility of GaAs which is a compound semiconductor well known for its high mobility. Recently, it was reported that mobility one further order of magnitude higher was obtained by improving sample preparation process. The high mobility reported by Geim and others has expanded the expectations that a high-speed transistor that would be impossible with conventional semiconductor materials could be realized by forming the electron transit layer in a transistor with graphene.

One of the major reasons why so many researchers have been attracted to graphene is that the limitation of Si LSI has appeared on the horizon. The highly successful progress of CMOS-based LSI technology has been achieved for many years by miniaturizing the process rule. The miniaturization of process rule and, at the same time, lowering the operation voltage of the transistors made it possible to integrate a larger number of transistors in LSI and to make operation of LSI faster without increasing power consumption ("Scaling Law"). The Scaling Law led a tremendous progress in Si LSI technology; the number of transistors in LSI has grown 100,000 times larger, and the operation speed has increased 30,000 times in thirty years from the early 1970s. As a result, research on compound semiconductors which were expected to replace Si has not been performed so intensively as expected at the beginning. However, the scaling down of the process rule of Si LSI is now thought to have come close to its limits. Therefore utilization of materials, such as CNT or graphene which exhibits much higher mobility than Si, has attracted attention as a key to improve LSI performance without scaling down the process rule.

[NOTE]
Mobility is a property indicating the mobile nature of charged particles including electrons in a solid. Higher mobility indicates that charged particles in a solid move faster.

Taking into account such trends, the International Technology Roadmap for Semiconductors (ITRS) committee has added carbon materials including CNT and graphene to the list of promising materials or technologies for future high-performance LSI, and has been discussing the feasibility. On the other hand, at a meeting held in 2009, the discussion was made under an assumption that the realization of graphene-based technologies would not come before 2019.[2] The meaning of this is that it will require a long time of research and development for the realization of graphene-based devices because, in spite of its wonderful potentiality, the research and development of graphene are still at an early and basic stage and there are still a number of technical challenges. For example, although some methods for graphene formation have been proposed, exfoliation of HOPG by scotch tape, the first method used for the formation of graphene, is still used in many reports on graphene-based transistors. This suggests that a practical method of forming high quality graphene has not yet been developed.

In this report, the following subjects concerning graphene will be focused on : general properties of graphene, widely-used graphene formation technologies, research on graphene-based transistors, and challenges for realization of graphene-based high-speed transistors.

1-2 Application Fields of Graphene

As already mentioned, the most attractive application field for graphene is high-speed transistors by taking advantage of its high-mobility, and many research efforts have been put into it. In addition to high mobility, graphene exhibits many other wonderful features and research to apply these features is also being intensively made. The features and the application fields are schematically shown in Figure 2. Some of the features and the application examples of graphene are listed below.

(1) Graphene exhibits the highest thermal conductivity and also the highest Young's modulus among the materials known so far (See Table 1). Making use of the high Young's modulus and the fact that it consists only of carbon, a light element, graphene-based NEMS (Nano Electromechanical System: electrically driven nanometer-size mechanical parts) has been reported to exhibit high vibration responsiveness.

(2) It is expected that adsorbed molecules on a graphene surface will easily affect the properties of graphene, compared with usual three-dimensional materials, because graphene is a two-dimensional material having no bulk volume under the surface. Therefore, applications of graphene to gas sensors are likely to achieve a high sensitivity and have been investigated.

(3) Although graphene is a one atom thick film, it is believed impermeable to almost all gas molecules including helium. Because of such characteristics, it is feasible to compose a pressure sensor by sealing a small opening with a graphene sheet and measuring the tension on the sheet.

2 Trend of Research Progress on Graphene

This chapter will show how research on graphene has extended, by analyzing the trends in the published papers and the presentations in academic conferences.

2-1 Trends of the Number of Research Papers

Figure 3 shows the trend of the number of published

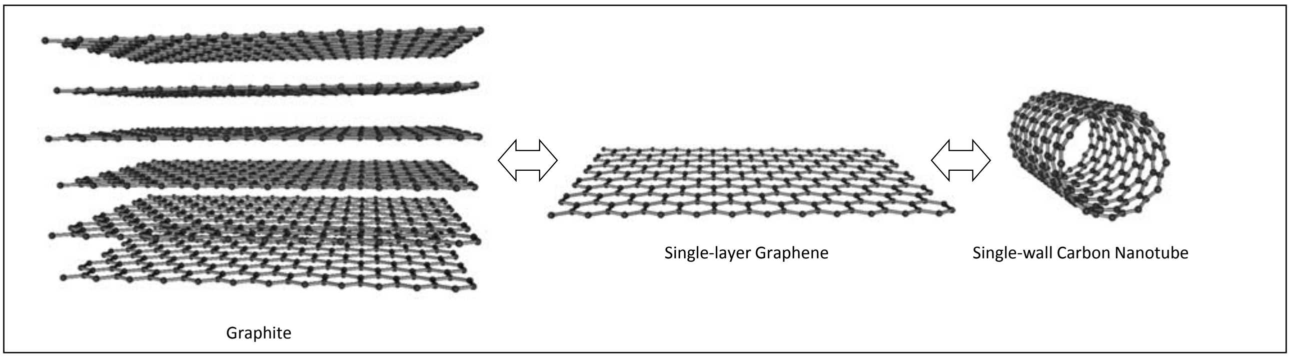


Figure 1 : Chemical Structure of Graphite, Graphene and Carbon Nanotube

Prepared by the STFC

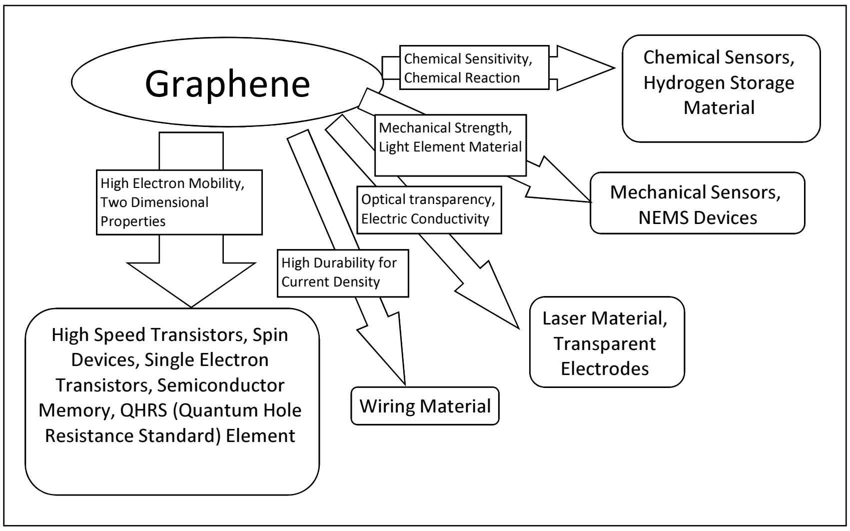


Figure 2 : Distinctive Properties of Graphene and Possible Application Fields

Prepared by the STFC based on the References[3–8]

Table 1 : Thermal Conductivity and Young's Modulus of Graphene and Typical Semiconductor Materials

Material	Thermal Conductivity	Young's Modulus
	W/cm・K	10^9Pa (GPa)
Graphene	～50	1500
Carbon Nanotube	～35	～1000
Diamond	10～22	1050～1200
Si	1.4	131
Ge	0.6	103
SiC	4.1	450

Prepared by the STFC based on Reference[3]

papers on graphene with regard to calendar year. They were retrieved out of the ISI Web of Knowledge database. The retrieval of papers was performed using the keywords "graphene" for the topic and "article" for the media. It is clearly shown in this figure that the number of papers has rapidly increased since the isolation of graphene was reported for the first time in 2004. In 2009, approximately 1,800 papers were published which is over 10 times larger than the number of papers in 2004. Before 2004, almost all of the retrieved papers were about CNT, and some were devoted to theoretical study of graphene.

Although some of the recent papers are on the performance of graphene-based devices, the majority of the papers are on the basic properties of graphene. This suggests that research on graphene is still at the early and basic stage. Figure 4 shows a trend analogous to Figure 3 by countries. The top 8 countries are taken in this figure, based on the number of papers from each country in 2009. The numbers of papers in 2009 are approximately 10 times as large as in 2005 for almost of all of these 8 countries. In the case of the US, the top in 2009, the number of papers is twice as large as the second country, and its increasing rate seems to be close to the world average, if we compare the trend with that of the world total shown in Figure 3. It is China and Korea that showed the highest increasing rate from 2005 to 2009. The rate is about 20 in the case of China. In the case of Korea, the number of papers was almost zero in 2005, but it was as large as 70 in 2009. Although Japan was second in 2005, and the number of papers from Japan in 2009 is 5 times as large as in 2004, it fell back to fourth in 2009.

Similar analysis was made for research institutions. Figure 5 summarizes the trend for 8 institutions which are the top 8 in 2009. The most distinctive institution in 2009 is the Chinese Academy of Science. The number of papers from the academy is almost 30% of all of the papers from Chinese institutions. It means that in China, submission of papers is concentrated in a limited number of institutions. On the other hand, in the US, although a large number of papers are submitted as a total, diverse institutions contribute to it.

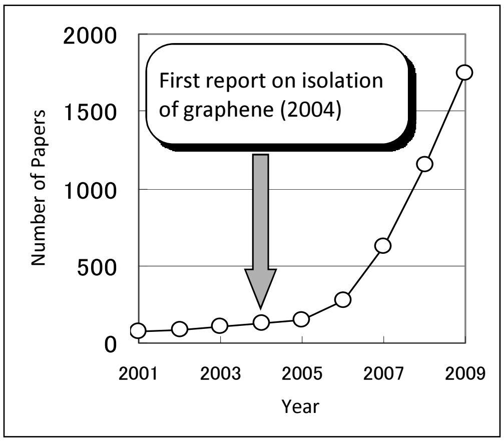


Figure 3 : Yearly Trends of Papers Regarding Graphene

Prepared by the STFC

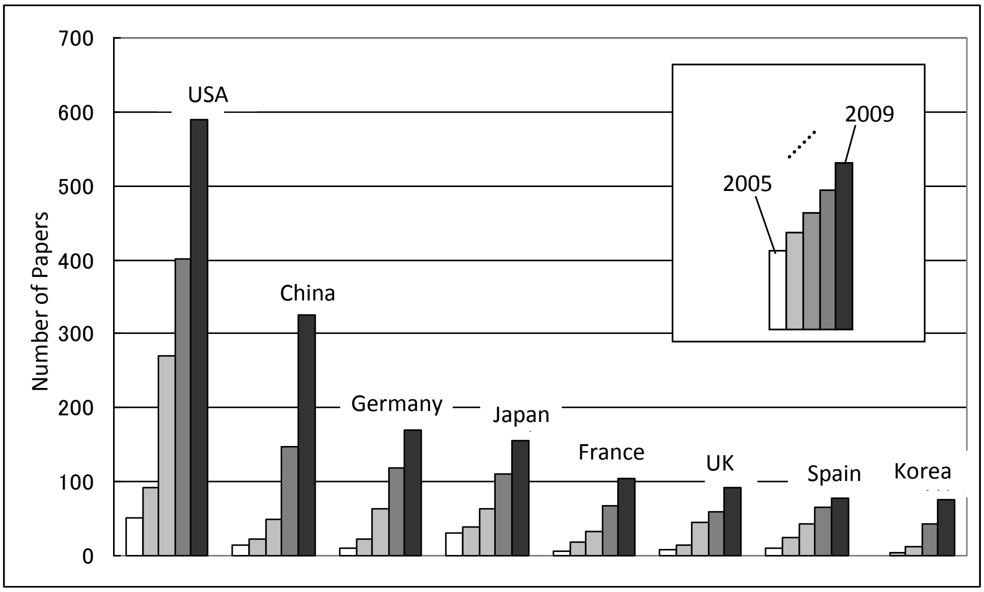
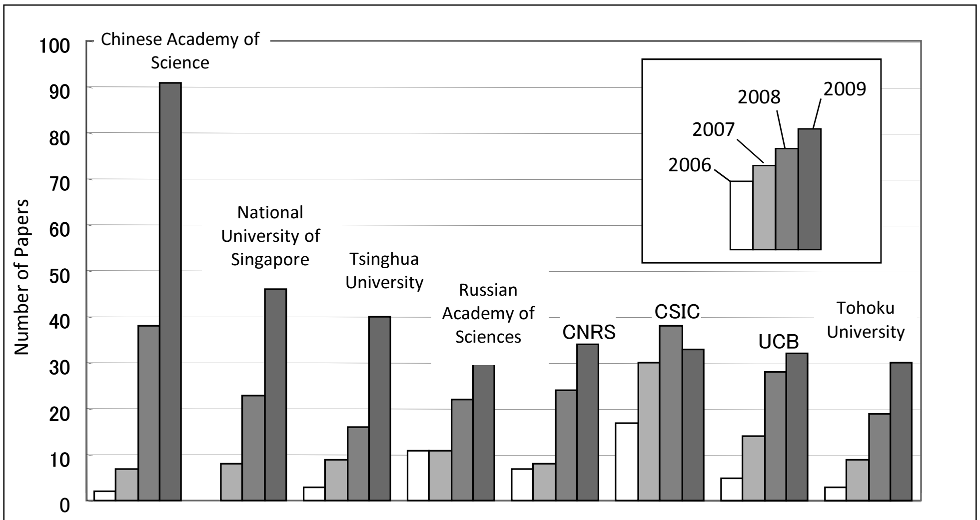


Figure 4 : Yearly Trends of Papers by Countries

Prepared by the STFC



CNRS: Centre National de la Recherche Scientifique (French National Center for Scientific Research),
CSIC: Consejo Superior de Investigaciones Científicas (Spanish National Research Council),
UCB: University of California, Berkley

Figure 5 : Yearly Trends of Papers by Research Institutions

Prepared by the STFC

2-2 Comparison between Conferences in US and in Japan on Graphene

Comparison between the numbers of presentations in recent academic conferences held in Japan and in the US will be made here. They are the 57th Spring Meeting of the Japan Society of Applied Physics held in March 2010 (hereinafter referred to as “JSAP”) and the Fall Meeting of Materials Research Society held from November through December 2009 (hereinafter referred to as “MRS”). Both of them are general conferences, covering various fields, and are held twice annually, in spring and fall.

Figure 6 summarizes the trends of the presentations at the conferences. In JSAP, the presentations on materials including CNT and graphene were performed at “Session Nanocarbon.” The number of the presentations in this session was 155. After classifying each presentation by its title into one of the categories, CNT, graphene, and others, 74 were on CNT, and 58 on graphene. That is, 132 presentations were on CNT and graphene. Almost all of the 58 presentations on graphene were from universities and public institutions. As for the presentations made by a private company (or companies) without collaborating with universities or public institutions, 5 were from NTT Corporation and 1 from Fujitsu Laboratories Ltd. Most of the presentations on graphene were on evaluation of basic material properties.

MRS had a session, “large-area electronics from CNT, Graphene and other materials.” There were 120 presentations made, nearly the same as that of JSAP. Out of them, 40 were on CNT and 80 were on graphene. Many more presentations were made on graphene than on CNT. This trend differs from JSAP. In the presentations made by US organizations or by collaboration with US organizations, 56 were on graphene, whereas 23 were on CNT. This ratio of graphene to CNT is slightly larger than that of the total of MRS. On the other hand, out of the presentations on graphene, 6 were on application to electronic devices, suggesting that, in the US as well as in Japan, most research activities are still confined around the basic area. Also, only 6 presentations on graphene were from private companies without collaborating with universities or public institutions, and public institutions and universities made most of the presentations. This trend is also seen in JSAP.

It can be concluded from the above analysis that the research activities on graphene are still at the early and basic stage, and are led by universities

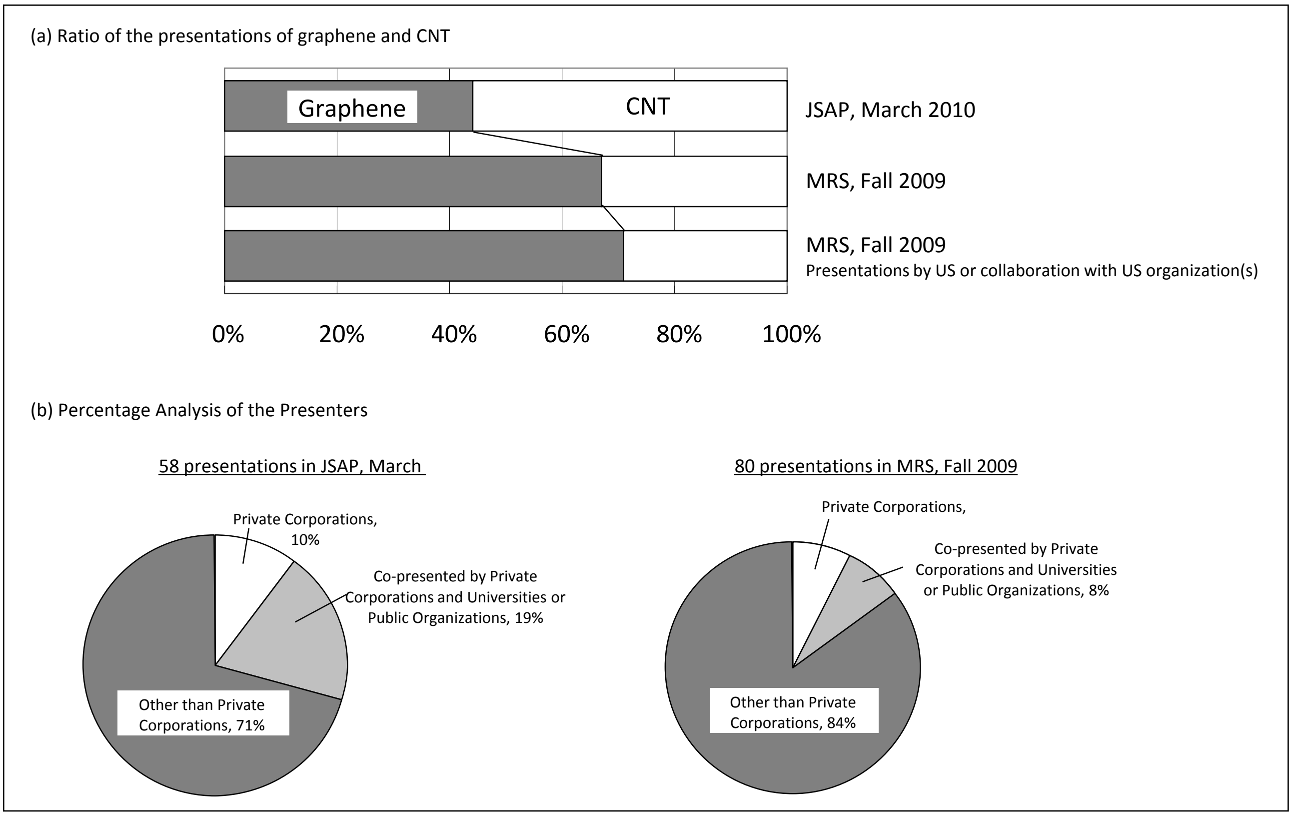


Figure 6 : Trends in the Presentations in Academic Conferences in US and Japan

Prepared by the STFC

or public institutions both in the US and in Japan. Concerning the applications for high-speed electronic devices taking advantage of the excellent properties of graphene, although there were not so many presentations, some of them are notable. Especially presentations by IBM seem to overwhelm the rest.

3 Electronic Properties of Graphene

This chapter will be devoted mainly to the introduction of the electronic properties of graphene, which is the key factor for the application to electronics. In addition, a brief comparison between graphene and CNT, which is also expected to be applied to electronics, will be made.

3-1 Electronic Properties

Figure 7 illustrates the band structure of graphene (b) in comparison with that of a typical semiconductor (a). An electron propagates as a wave in a crystal. A band structure illustrates the relation of the wave number to the energy of electrons in a crystal. Electrons in a crystal successively occupy from the lower states to the upper in the band structure (from the lower part to the upper part in the figures). As is shown in Figure 7 (a), the band structures of a typical semiconductor splits into two bands, the upper and the lower. Usually, there are almost no electrons in the upper band, and there are almost no vacancies of electrons (holes) in the lower band. The upper and the lower bands are called the conduction band and the valence band, respectively. Between the conduction band and the valence band, there exists an energy zone where there are no states for electrons to occupy, which is called a bandgap. In Figure 7 (c), the bandgap and electron mobility at room temperature for several semiconductors are summarized.

The band structure of graphene differs from that of a typical semiconductor in the following points:

(1) at around the point where the conduction band and the valence band meet each other, the slope of the band structure is linear ;
(2) the conduction band is connected continuously with the valence band, which means the bandgap is zero.

With respect to characteristic (1) of the band structure, in the case of a typical semiconductor, the band structure at around the top of the valence band and the bottom of the conduction band shows a parabolic shape and the slope changes gradually. The larger the change of the slope of the band, the less the effective-mass of the electrons (virtual mass of electrons in a material). On the other hand, in the case of graphene, because the slope is linear, the effective mass of electrons is zero. This means that graphene shows very high electron-mobility. A theoretical expectation of the electron-mobility of graphene is 1,000 times higher than that of silicon, and an electron mobility as high as $2\times10^6 cm^2/V$ sec[10,11] has been experimentally achieved, which is 100 times higher than that of silicon. Because higher electron mobility leads to shorter switching time for a transistor, graphene has been expected as a material that could realize high-speed electronic devices which could break the speed records made by conventional semiconductors such as silicon or compound semiconductors. For that reason, graphene has been expected to be applied to high speed-transistors. In addition, graphene has been paid much attention as a target of physics because the zero effective mass in graphene is a special quantum mechanical phenomenon.[3,12]

On the other hand, the zero bandgap in graphene, mentioned in (2), means that a very small thermal energy excites electrons out of the valence band up to the conduction band. Therefore, graphene cannot be kept semi-insulating. In general, materials should be controlled to have high electric impedance for high signal intensity when applied to digital devices, because digital devices are required to have a high switching on/off ratio. Therefore, the zero bandgap of graphene is a very high hurdle for application to digital transistors. Several methods are proposed to open the bandgap of graphene, and some experiments have been reported to succeed to tune the bandgap, which will be mentioned in 5-1. Generally speaking, the wider bandgap of graphene is achievable by deforming, more or less, the band structure illustrated in Figure 7 (b), and may therefore easily result in diminishing the advantage of high electron mobility. In this respect, it is a big challenge for the technology development of graphene, to make the bandgap wider without diminishing the high electron mobility.

3-2 Comparison with Carbon Nanotube (CNT)

Because CNT has the same atomic arrangement as graphene except that CNT is cylindrical (Figure 1), it shares many properties with graphene such as high electron mobility. CNT and graphene differ from each other in the following points:

(1) Graphene is more compatible with the conventional semiconductor manufacturing process than CNT because graphene is provided as a two-dimensional film while CNT is as one-dimensional fibers;

(2) CNT changes its properties from that of metal to semiconductor depending on a slight change in the atomic arrangement. In order to use CNT for electronic devices, it is necessary to collect CNT pieces that show semiconductor properties. The separation process of nanometer sized samples seems to be quite a serious bottleneck in manufacturing. Recently, methods to make or to separate CNT of metal or semiconductor properties have been developed. Some reports showed separation of CNT with as high as 90% purity. However, this figure is not sufficient from the standpoint of device manufacturing;

(3) The advantage of CNT is that a single piece

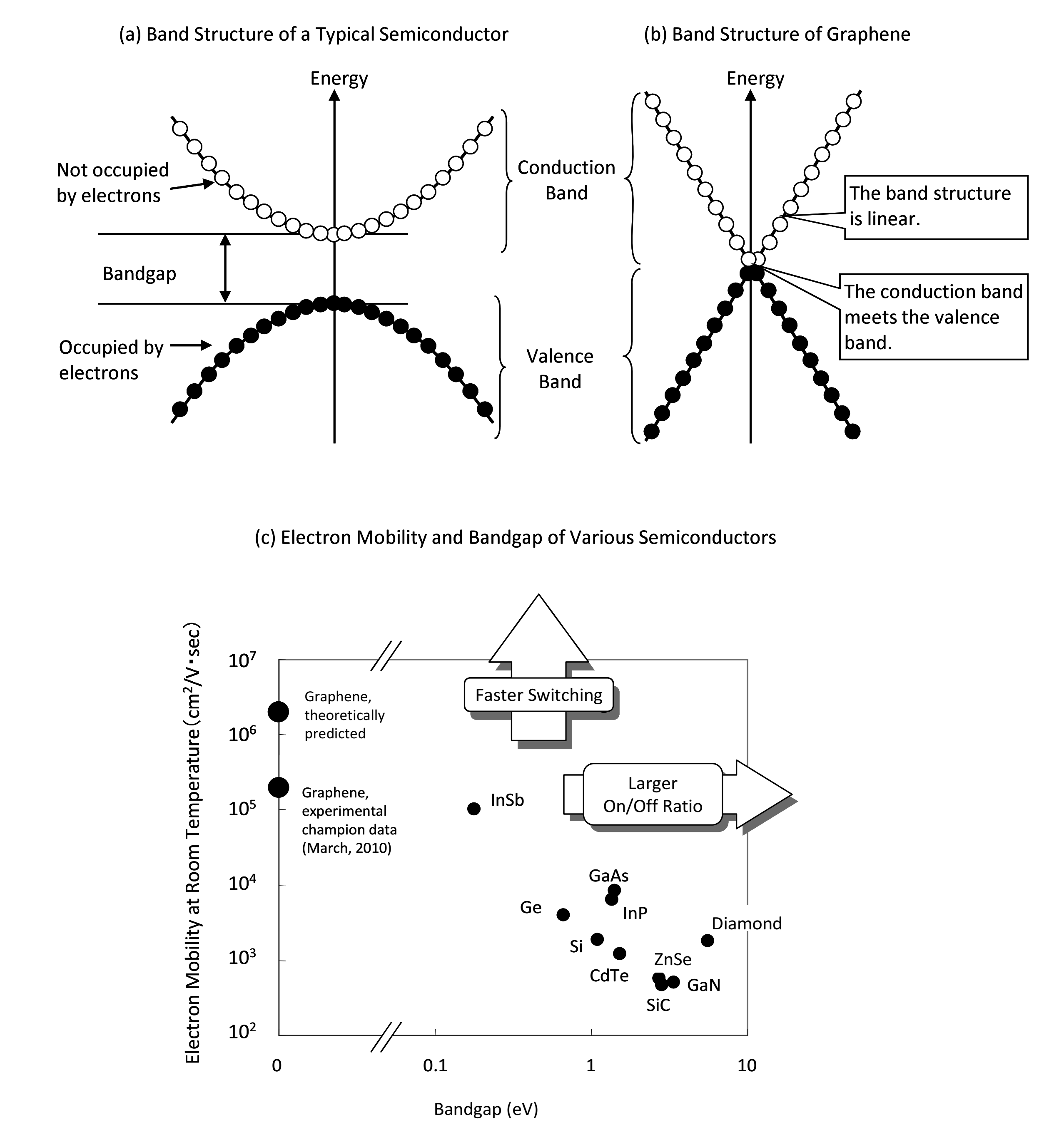


Figure 7 : Band Structures of a Typical Semiconductor (a) and Graphene (b), and Electron Mobility and Bandgap of Several Semiconductors (c)

Prepared by the STFC based on Reference[9] of CNT can be used for the device fabrication directly, whereas graphene should be processed to have semiconducting nature before device fabrication.

4 Growth and Evaluation Methods of Graphene

4-1 Production Methods

Some widely used or important production methods of graphene will be reviewed in this section. Among them, mechanical exfoliation of HOPG and conversion of SiC surface have been reported to be effective for better transistor properties than others. However, no production methods to form large-area uniform graphene sufficient for the fabrication of devices have been developed so far.

4-1-1 Exfoliation of Highly Oriented Pyrolytic Graphite (HOPG)

HOPG, which is generally prepared through high-temperature treatment of organic compounds, has a crystalline structure where graphene layers are stacked. A graphene layer is easily peeled off because there is only weak, van der Waals, force between the layers.

By utilizing this property, Geim and his coworkers successfully isolated graphene by repeatedly exfoliating HOPG with scotch tape.[1] The isolated graphene was transferred onto another appropriate substrate finally. This process is illustrated in Figure 8 (a). This method is quite simple as easily can be seen in this figure. Some video websites on the Internet provide movies of the process. Figure 8 (b) shows an optical microscopic photo of graphene obtained by this method.

Generally, the half-width of X-ray diffraction (X-ray rocking curve) peak of HOPG is around 0.4 degrees, which is roughly two orders of magnitude larger than that of a typical semiconductor. This means that the crystalline quality of HOPG is very low compared with other semiconductor crystals. This low crystallinity seems to indicate that HOPG consists of many small crystals (domains) and that the directions of domains are rather scattered. Therefore, it is not realistic by the exfoliation of HOPG to obtain a graphene flake of larger area than the domain size of HOPG. Furthermore, it is not practicable to exfoliate HOPG with a thickness precision of a single atomic layer. As a result, the obtained continuous sample of graphene consists of various parts of a different number of layers. The optical microscopic observation photo in Figure 8 (b) shows such a situation clearly.

Exfoliation is performed manually and in an ordinary atmosphere. So, it would be considered highly possible that impurities and adsorbates on the surface of graphene or mechanical damages will have much influence in the sample formed by this method. However, so far, the samples obtained by exfoliation have often shown higher mobility than that of samples obtained by other methods.

Because the exfoliation method is simple and convenient and, at the same time, the material properties of obtained samples are relatively good compared with those obtained by other methods, almost all of the reported devices have used graphene obtained by exfoliation. Although the exfoliation method has a drawback in that it is hard to obtain a large-area sample for practical use, it will remain as a sample production method for the proof-of-concept devices.

Another method using HOPG, where HOPG is ultrasonicated in organic solvent, has been reported.[3] Because the graphene obtained by this method is suspended in the solvent, a thin graphene film is obtained by applying the graphene containing solvent to a substrate. However, high-quality graphene for device fabrication and evaluation would not be obtained by this method.

4-1-2 Surface Conversion of Silicon Carbide (SiC) by Heat Treatment

It is reported that heat treatment of SiC in a vacuum or in an inert atmosphere forms a graphene layer on the SiC surface,[13] which is a result of evaporation of silicon atoms from the SiC surface and of resultant segregation of carbon atoms on the surface. This method has been expected to be suitable for the preparation of high-quality graphene, because high-quality SiC wafers for semiconductor manufacturing are commercially available, and process in a vacuum or in an inert atmosphere diminishes the undesirable influence of impurities. However, there have been no reports of high-performance devices by this method until recently.

Due to the polarity of SiC crystal, a generally available SiC substrate has two faces, i.e. a silicon face and a carbon face. Properties of graphene obtained

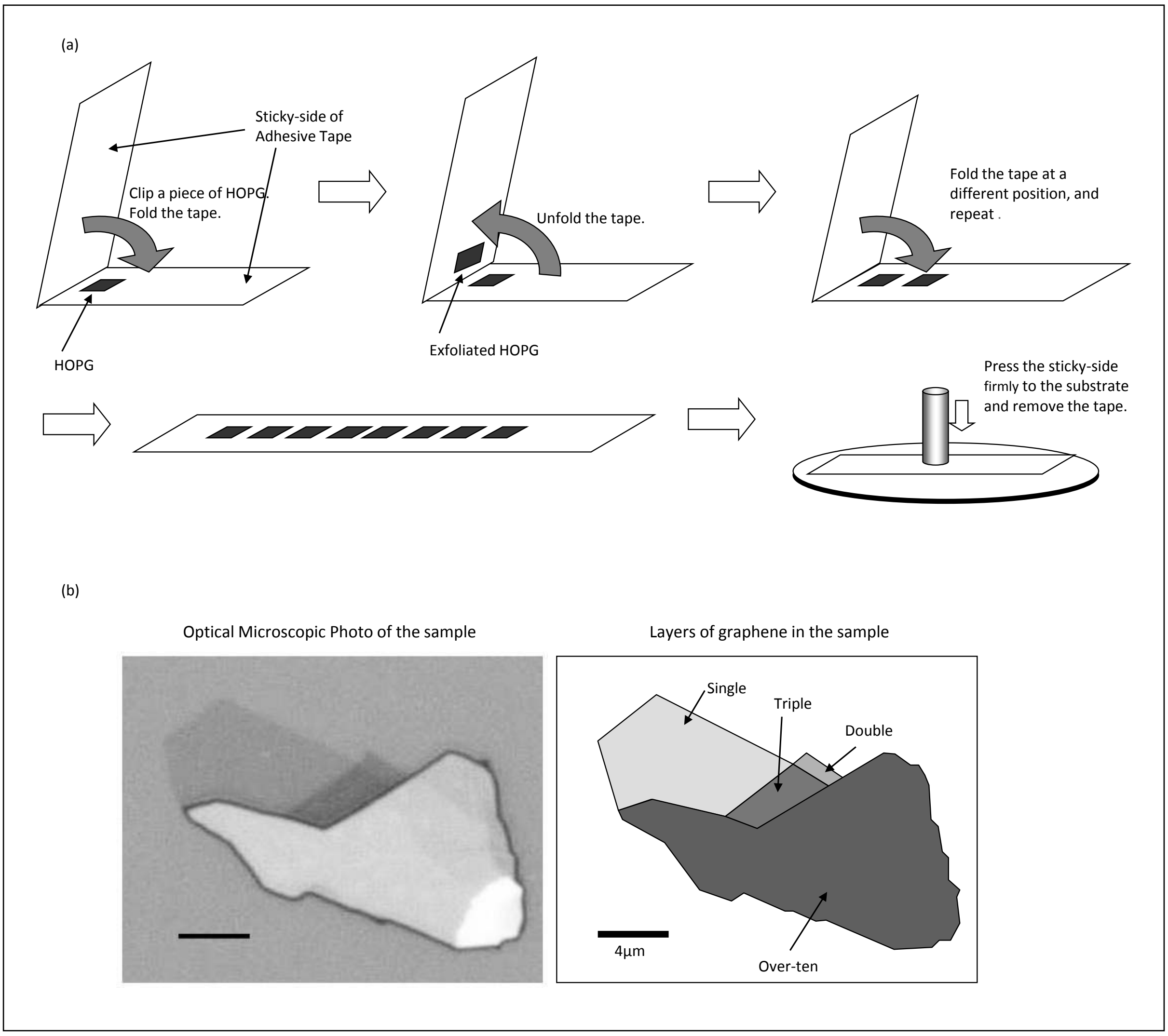


Figure 8 : (a) Illustration of Exfoliation of HOPG by Using Adhesive Tape, (b) Optical Microscopic Photo of Isolated Thin Graphene Film

(a) Prepared by the STFC
(b) Courtesy of Dr. Hisao Miyazaki, International Center for Materials Nanoarchitectonics, National Institute for Materials Science

by heat treatment depend on the type of the substrate face, as well as heat treatment conditions such as temperature, duration or atmosphere. Although the quality of the graphene obtained by this method has been improved by tuning the process conditions, the size of the single domain of uniform layer thickness has not exceeded several micrometers. Although the start material is a high-quality semiconductor wafer, the short range thickness uniformity is inferior to that of graphene made by exfoliation of HOPG, in some cases.

A similar method using SiC has been reported where a vapor-phase-grown SiC epitaxial film on a silicon substrate is heated to form graphene.[14]

4-1-3 Vapor-Phase Deposition Method

Generally, CVD (Chemical Vapor Deposition), a method supplying raw material gas onto the heated substrate to form a film, is suitable for the uniform film-formation in large area, and has been widely applied to a variety of semiconductor thin films.

Applying CVD to graphene, a hydrocarbon-type organic compound such as methane or acetylene is used as a raw material. Because such an organic gas does not easily decompose thermally, the substrate needs to have a catalytic capability of decomposing the gases. Copper foils,[15] metals[16] such as nickel deposited on a SiO_2/Si substrate or sapphire[17] have been reportedly used for the substrate. Electron mobility as high as 4000 cm^2/V sec has been reported by using copper as a substrate. However, the reported value, while higher than that of silicon, is one order of magnitude smaller than the value obtained with the graphene prepared by exfoliation of HOPG or heat treatment of SiC. In addition, there are only a few reports on the fabrication of electronic devices of

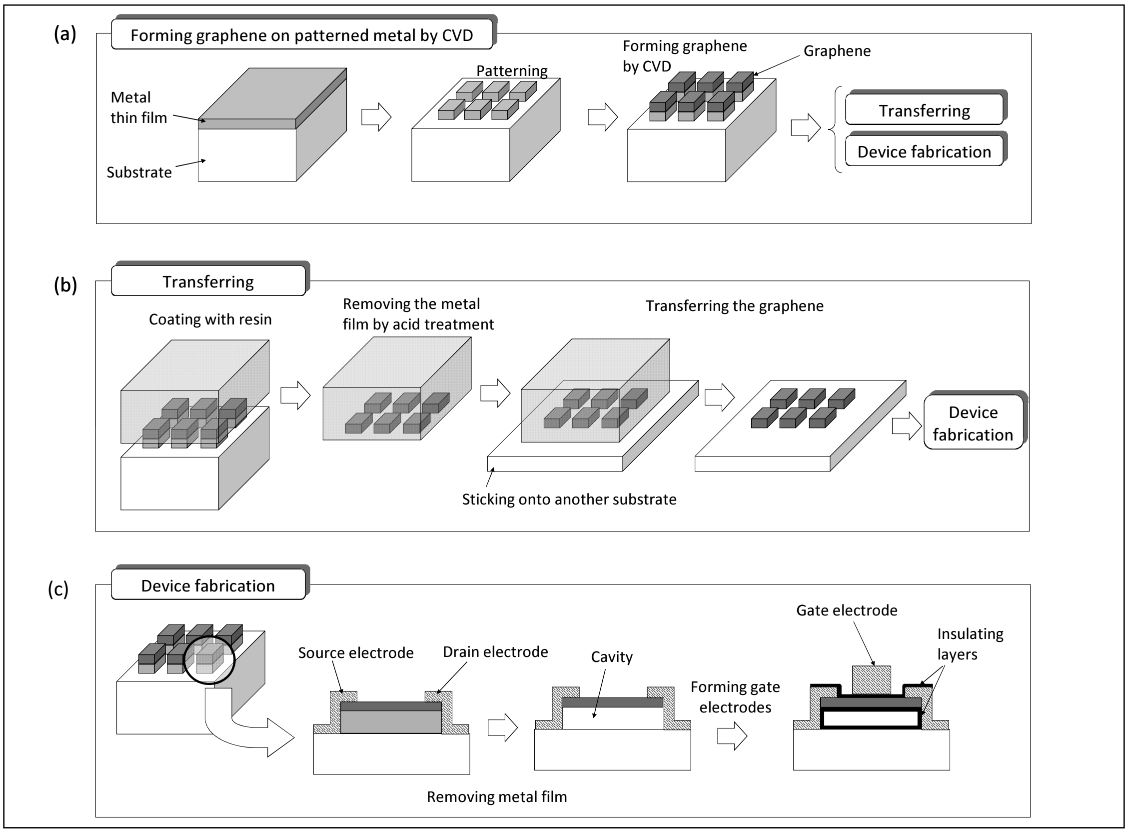


Figure 9 : Formation of Graphene on Patterned Catalytic Metal Thin Film

Prepared by the STFC based on Reference[16,18]

CVD graphene.

With respect to copper as a substrate material, because the number of graphene layers did not increase even if the deposition time was prolonged, there seems to be a kind of self-limiting mechanism in the CVD reaction. However, the obtained sample contains more than 5% of a multilayered region, which implies that the self-limiting mechanism is not strict in this case and is not good enough from the viewpoint of semiconductor device fabrication. On the other hand, if the self-limiting mechanism is perfect, it is not applicable to the process where multilayered film is required.

A problem of employing metal substrates is that electric evaluation cannot be accomplished on a metal substrate due to its electric conductivity. The deposited graphene has to be isolated by dissolving the metal substrate in an etchant solution and then transferring it onto an insulating substrate for electric evaluation. For example, a method has been reported such that, after protecting the surface of the deposited graphene on a metal substrate with acrylic resin (PMMA) and removing the metal substrate to leave the graphene on the resin, the graphene left on the resin is transferred onto another substrate. On the other hand, when an insulating material like sapphire is used for the deposition substrate, fabrication and evaluation of the devices on the substrate can be made simply.

Figure 9 illustrates an example of a series of processes from graphene film formation by CVD to device fabrication. In Figure 9(a), a process of graphene film formation on patterned metal is illustrated. Graphene film of any desired pattern is formed by patterning the metal prior to the deposition. Figure 9(b) illustrates a process of transferring the deposited graphene film of (a) onto another substrate. After transferring the film, devices are fabricated.

Very recently, a new process, illustrated in Figure 9(c), has been reported,[18] which enables direct device fabrication of the CVD deposited graphene film on the patterned metal without transferring. The graphene film formed on metal by the process of Figure 9(a) is subjected to the process illustrated in Figure9(c). In the process of Figure 9(c), electrodes are formed on the graphene films at first, then the catalytic metal is removed by acid treatment and finally transistors are formed. The process has such an advantage over other processes that it is free from the risk of the substrate removing process and transferring the graphene, and, at the same time, cuts down the overall processing time. In addition, the process has various advantages over the processes where transferring the film is necessary, because it enables performing a series of processes continuously on a desired substrate. It is probable that this new process would be standard for the fabrication of transistors.

4-1-4 Other Film Formation Methods

Oxidized graphene is water-soluble. By applying ultrasonication to the solution of oxidized graphene, graphene is exfoliated in the solution. After centrifugal separation, applying the oxidized graphene solution on a substrate and then reducing, the film is converted to graphene.[3] It has been also reported that ribbon-shaped graphene (graphene nanoribbon) is formed by unzipping of CNT by chemical reactions.[19,20] However, the abovementioned methods are not likely applicable to a semiconductor process because they are not film formation methods on a substrate.

4-2 Evaluation Methods

It is disadvantageous for graphene that the evaluation methods of crystallinity or impurities that have been widely used for the conventional semiconductors are not applicable.

Because the crystallinity and impurities in a material are key factors determining the device characteristics of the semiconductor devices, they are generally the first subjects to be evaluated.

Scanning tunneling microscope (STM) observation, X-ray diffraction, chemical etching, photoluminescence, or others have been widely used for the characterization of conventional three-dimensional crystal materials. However, X-ray diffraction or chemical etching is not applicable to graphene because graphene is two-dimensional layered material. Furthermore, photoluminescence analysis is not applicable because its bandgap is zero. Although there have been some reports on the defects in graphene studied by STM, STM is not a versatile method for the evaluation of crystallinity for general purposes.

Currently, observation of morphology by optical microscopy, evaluation of film quality by Raman spectroscopy, or evaluation of layer structure by Raman spectroscopy or electron microscopy are commonly used methods for the characterization of graphene. Concerning the material properties, graphene has been evaluated mainly through electrical measurements. However, results of those measurements on graphene are so largely dependent on the conditions of measurement or sample preparation that, in some cases, it is not certain whether the results really reflect the properties of the sample itself.

4-3 Film Forming Methods to Be Developed

For semiconductor crystal growth (film formation), a uniform and high-quality film over the entire area of the substrate is generally required. As for graphene, film thickness controllability to the level of a single atomic layer is additionally required. Three examples of film forming methods given below seem to give us some insights into the abovementioned requirements. Knowledge and expertise on chemical reactions and organic synthesis will play an important role in developing each of these methods.

For the single atomic layer control of the film thickness, the following two methods are well known: in the Langmuir-Blodgett method, a mono-atomic layer floating on the solvent surface is transferred onto the substrate, and in the ALD/ALE (Atomic Layer Deposition / Atomic Layer Epitaxy) method, CVD with perfect self-limiting of the film formation is realized. Because those methods well utilize the chemical behavior of materials, they require knowledge or expertise on molecules' chemical nature or reactions.

There have been some reports on organic synthesis of graphene-like structures.[21] The advantages of these methods are that the edge atoms or groups of the structure can easily be replaced with other atoms or groups, and that a chemically well-defined substance could be obtained. Figure 10 illustrates an example of a synthesized ribbon-shaped graphene-like substance. However, samples that can stand for the evaluation of material properties have not been reported. Furthermore, as for the single layer formation on a desired substrate, almost no progress has been made.[22]

4-4 Formation and Control of Interface

As already mentioned, graphene consists solely of surface, not having a bulk volume under the surface. Therefore, the material properties of graphene are susceptible to environmental conditions. Although such susceptibility may be advantageous for application to gas-sensors, it is largely disadvantageous for application to electronic devices. It has also been reported that, to achieve high mobility, thermal annealing[10] to get rid of adsorbates

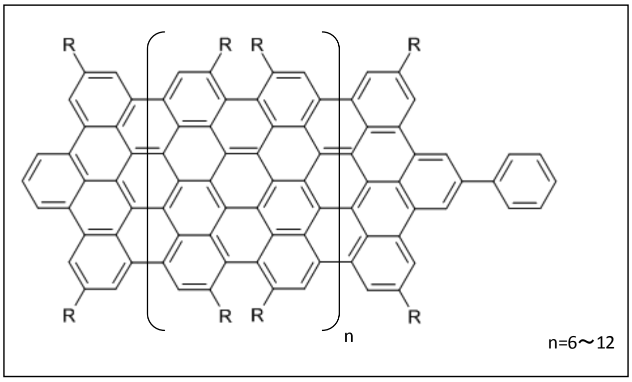


Figure 10 : Molecular Structure of Ribbon-Shaped Graphene-Like Substance Obtained by Organic Synthesis

Prepared by the STFC based on Reference[21]

is important. Therefore, practical devices would not be available without preparing countermeasures against environmental disturbance.

Concerning influence from the environment, the properties of graphene are also influenced by the substrate as well as by the adsorbates. For example, it has been reported that one order of magnitude higher mobility was obtained[10] by suspending the graphene sample off of the substrate like a bridge, compared to the case where graphene directly contacts the substrate. It is considered that the impurities in the substrate cause decrease in mobility when the graphene has direct contact with the substrate. From a practical point of view, development of protecting films against atmospheric interference which do not affect the material properties is crucial.

5 Research and Engineering on Graphene-based Electronic Devices: Current Status and Trends

In this chapter, control methods of bandgap of graphene will be described first, and then an overview on graphene-based electronic devices of which application has been studied will be given. The electronic devices are a field effect transistor utilizing high mobility of graphene, a single-electron transistor utilizing switching capability by loss or gain of single electron, and a spin-transport device which transports an electron's spin-state.

5-1 Opening and Tuning of Bandgap

As mentioned in 2-1, the zero bandgap of graphene makes it hard to be applied to digital devices which require a high switching on/off ratio. Two techniques listed below are mainly studied for opening the bandgap.

5-1-1 Bilayer Graphene

Bilayer graphene is a lamination of two layers of graphene. Although the bandgap of bilayer graphene is still zero, it can be opened by applying an external electric field across the bilayer graphene (Figure 11). Adsorption of atoms such as potassium on the bilayer graphene is also effective for opening the bandgap similarly.

Usually a band gap is a material parameter which is determined uniquely to each material as shown in Figure 7(c). In this respect, the method where an electric field is applied to bilayer graphene is not only advantageous but also of great interest in that the bandgap is tunable by the applied field strength. It has been reported that the bandgap was tuned up to about 0.3 eV.[23] According to another report,[24] widening of the bandgap has also been confirmed by measuring electric properties of the transistors fabricated by using bilayer graphene.

It is known that the electron mobility in bilayer graphene is lower than that of single layer graphene. A computer simulation,[25] however, reported that transistors based on such bilayer graphene would perform high speed operation as fast as HEMT (High Electron Mobility Transistor) made of InP which is a compound semiconductor known for its high electron mobility.

5-1-2 Graphene Nanoribbon

Another technique for opening the bandgap of graphene is to decrease the width of a graphene sheet. Graphene is called a graphene nanoribbon when the width of the graphene is several times the unit cell of graphene. Theoretical calculations[26] on the band structure of graphene nanoribbons have shown that graphene nanoribbons exhibit metallic properties or semiconductor properties, i.e. the bandgap is larger than 0, depending on the orientation of the ribbon. Two configurations of graphene nanoribbon structure are illustrated in Figure 12 (a) and (b) focusing on the edges of graphene nanoribbons. The configuration illustrated in (a) is called the armchair type where the edge has a cyclic structure of four carbon atoms, i.e. two couples of carbon atoms. A graphene nanoribbon of the armchair type configuration exhibits semiconductor properties. On the other hand, the

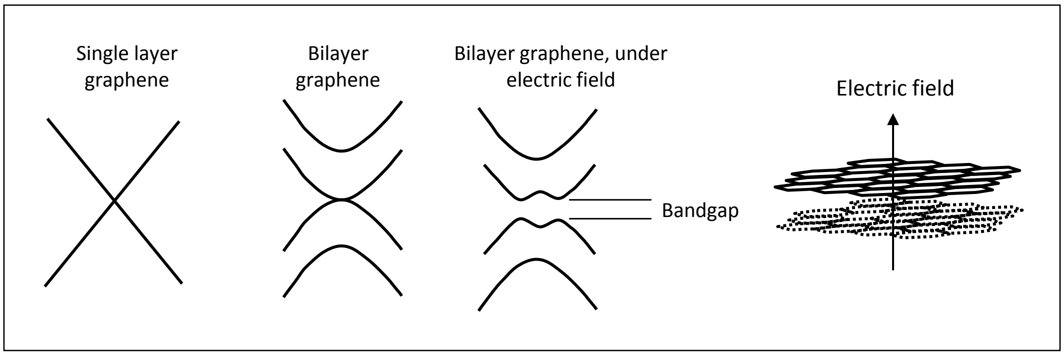


Figure 11 : Band Structures of Single Layer Graphene, Bilayer Graphene and Effect of Electric Field

Prepared by the STFC based on Reference[23]

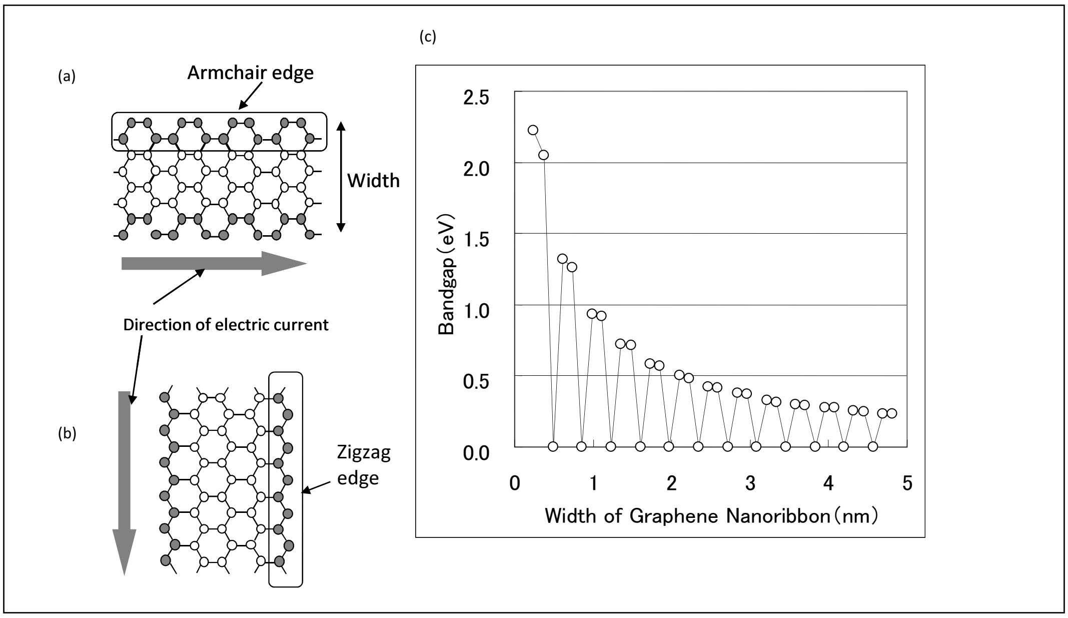


Figure 12 : Illustration of Two Types of Edges, (a) Armchair Edge and (b) Zigzag Edge, and (c) Theoretically Calculated Bandgap of Armchair-Edged Graphene Nanoribbon

Prepared by the STFC based on Reference[27]

configuration in (b) is called the zigzag type where the edge zigzags. A graphene nanoribbon of the zigzag type configuration exhibits zero bandgap.

Figure 12(c) illustrates a relationship between the bandgap and the width of the armchair type graphene nanoribbon obtained by a theoretical calculation.[27] Although the bandgap changes cyclically with the width, the general trend of bandgap is an increase with decreasing the width. Here it should be noted that the bandgap can fluctuate largely even by a slight change in the width. Therefore, it is thought that bandgap control by the nanoribbon width will require very fine fabrications of a nanometer or smaller precision in both width and orientation.

However, on the contrary to such theoretical predictions, the measured relationship between the bandgap and the width of graphene nanoribbons fabricated by fine processing technique did not show dependence of the bandgap on the orientation of the nanoribbons.[28] It is suspected that the fabricated samples contained defects, that the edges contained various shapes, or that the samples were not chemically uniform. Therefore, the results also seem to suggest that the fabrication technology was not matured to a level required for the realization of graphene nanoribbon electronic devices.

Recently, two experimental reports were published on the methods to control the bandgap similarly to the method using nanoribbons. The first method is to fabricate the graphene into a mesh by densely making many small holes with a radius of about 10 nm on the graphene. The idea of the mesh-structured graphene,[29] named “graphene nano-mesh” by the inventors, is to widen the bandgap by adjusting the width of the graphene in the “neck,” the part between the holes, to several nanometers. Another method is to form nanometer scale high-impedance regions on the graphene sample with high density, by adsorbing hydrogen atoms locally on the surface of the graphene sample.[30] Unlike the nanoribbon method, neither of the two methods requires narrowing the width of the original graphene sheet. Therefore, the graphene made by those methods can endure high electric current, and the handling of these substances is easier than nanoribbons. According to these advantages over nanoribbons, attention will be paid to their development.

5-2 Field Effect Transistor

The field effect transistor (FET) is a key element of LSI, where the current flowing through a thin channel layer is controlled by gate electrodes. FET can be operated faster with a channel layer of a higher electron mobility material, which is the very point of the application of graphene to FET.

There are some reports on the characteristics of FET using graphene as a channel layer material. For the fabrication of graphene-based FET, graphene exfoliated from HOPG is often used. On the other hand, a recent report on 100 gigahertz operation[4] of a FET based on graphene by heat-treatment of SiC, has been a major topic. The operation speed is already more than twice higher than that of silicon-based FET which uses silicon as the channel layer with the same gate length. It strongly indicates the high potentiality of graphene application to FET.

In addition, the mobility of graphene used in these reports is not so high compared with that expected of typical graphene samples. In another report,[31] it was mentioned that the mobility was lowered to a great extent after processing for FET fabrication. It suggests that, establishing a process that can preserve the high mobility that graphene originally possesses, and improvement of the FET structure matched to the properties of graphene, will make graphene-based FET terahertz operation possible, which has not been realized by FETs based on other materials.

5-3 Single-Electron Transistor

Electronic states of metals or semiconductors sized some nanometers three-dimensionally can be changed drastically by injecting only a single electron into it. Such a very small structure is called a quantum dot. The electronic states of a quantum dot can be controlled also by controlling the electric potential of the quantum dot. The single electron transistor (SET) is based on the idea of controlling the number of electrons in a quantum dot by its electric potential. The energy consumption of SET is thought to be very small, because the unit of information is a single electron. Therefore, SET is expected to be a transistor which will be used widely in the future, and many research efforts have been put into it.

There are some reports on application of graphene to SET, and switching at room temperature has been reported.[6] Graphene has a potential advantage that quantum dots can be easily formed just by cutting out small regions by etching, because graphene originally has only a single atomic layer thickness. However, controllable fabrication with a precision of several nanometers still remains as a challenge. For example, the switching performance at room temperature is not well reproducible yet due to the lack of precise fabrication technology.

5-4 Spin Transport Device

In the spin transport device, information is carried as a form of flow of electron-spin polarity. It has been thought that such a device has various advantages over the conventional devices using electric current, and several materials have been research targets. Graphene has been expected to be applied to the spin transport device, for the reason that the spin polarity of an electron in graphene is less perturbed by nuclei because graphene contains only carbon atoms, one of the light elements. A report[5] has already experimentally shown that spin injection into graphene is attainable. Furthermore, it has been observed that the electrons diffuse in graphene keeping the spin polarity. It is certain that graphene is considered to be one of the promising candidate materials for the spin transport device.

6 Conclusions

In recent years, graphene has attracted attention as a promising material for advanced electronic devices including high speed transistors which play a central role in LSI technology, and the number of articles on graphene has been increasing rapidly. However, in reality, the technologies of fabrication or processing are far from the level expected for the actual production of devices for practical use. As for such fabrication technologies, film forming process technologies with one-atom thickness precision are required. In addition, there is a need for development of process technologies for device fabrication with atomic level precision, which are required to control the chemical state of the graphene edges while preserving the properties of graphene. Furthermore, those process technologies must include technologies for protecting graphene in order to preserve the high quality of graphene against the environment, because the properties of graphene, having no bulk volume, are very susceptible to the surface conditions. In addition, those technologies would not be applicable if they do not provide production-level uniformity for electronic devices. There is a need to develop manufacturing technologies that satisfy these requirements for taking advantage of graphene's fascinating properties.

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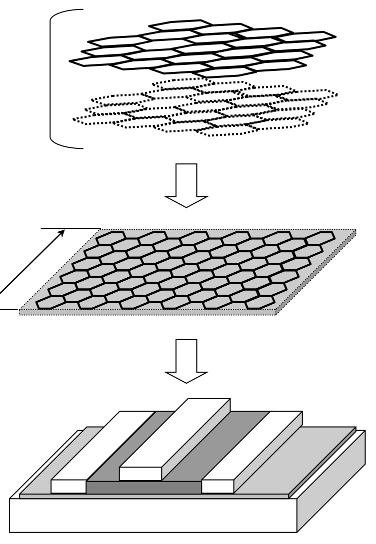

Figure 13 : Production Process Technologies Required for Fabrication of Electronic Devices Based on Graphene

Prepared by the STFC

References

[1] K. S. Novoselov et al., "Electric Field Effect in Atomically Thin Carbon Films," Science, 306 (2004) 666.

[2] Homepage of ITRS: http://www.itrs.net/Links/2009Winter/Presentations/Conference/ERM_121609.pdf.

[3] A. K. Geim, "Graphene: Status and Prospects," Science, 324 (2009) 1530, and references therein.

[4] Y. -M. Lin et al., "100-GHz Transistors from Wafer-Scale Epitaxial Graphene," Science, 327 (2010) 662.

[5] M. Ohishi et al., "Spin Injection into a Graphene Thin Film at Room Temperature," Jpn. J. Appl. Phys., 46 (2007) L605.

[6] L. A. Ponomarenko et al., "Chaotic Dirac Billiard in Graphene Quantum Dots," Science, 320 (2008) 356.

[7] Homepage of the National Institute of Advanced Industrial Science and Technology: http://www.nmij.jp/~nmijclub/teishuha/docimgs/oe_20080730.pdf.

[8] H. Zhang et al., "Large energy soliton erbium-doped fiber laser with a graphene polymer composite mode locker," Appl. Phys. Lett., 95 (2009) 141103.

[9] "Group III-V Compound Semiconductors" I-1, Advanced Electronics Series, authored and edited by Isamu Akasaki, Baifukan, 2002 (Japanese), Refer to chapter 13 for GaN and chapter 7 for others.

[10] M. Orlita et al., "Approaching the Dirac Point in High-Mobility Multilayer Epitaxial Graphene," Phys. Rev. Lett., 101 (2008) 267601.

[11] K. I. Bolotin et al., "Ultrahigh electron mobility in suspended graphene," Solid State Commun., 146 (2008) 351.

[12] A. K. Geim et al., "Carbon Wonderland," Scientific American, 298 (2008) 90.

[13] K. V. Emtsev et al., "Toward wafer-size graphene layers by atmospheric pressure graphitization of silicon carbide," Nature Mater., 8 (2009) 203.

[14] Y. Miyamoto et al., "Raman-Scattering Spectroscopy of Epitaxial Graphene Formed on SiC Film on Si Substrate," e-Journal of Surface Science and Nanotechnology, 7 (2009) 107.

[15] X. Li et al., "Large-Area Synthesis of High-Quality and Uniform Graphene Films on Copper Foils," Science, 324 (2009) 1312.

[16] K. S. Kim et al., "Large-scale pattern growth of graphene films for stretchable transparent electrodes," Nature, 457 (2009) 706.

[17] Makoto Okai et al., "Growth of Graphene on Sapphire Substrate by Thermal CVD," the 70th Fall Meeting, 2009 11p-ZR-3, Japan Society of Applied Physics (Japanese).

[18] D. Kondo et al., "Low-Temperature Synthesis of Graphene and Fabrication of Top-Gated Field Effect Transistors without Using Transfer Processes," Appl. Phys. Exp., 3 (2010) 025102.

[19] D. V. Kosynkin et al., "Longitudinal unzipping of carbon nanotubes to form graphene nanoribbons," Nature, 458 (2009) 872.

[20] L. Jiao et al., "Narrow graphene nanoribbons from carbon nanotubes," Nature, 458 (2009) 877.

[21] Kentaro Satoh, "Chemical Synthesis Challenges New Carbon Materials from Graphene to Nanotubes," Gendai Kagaku (Modern Chemistry), August 2009, pp.16-20, and references therein (Japanese). See also, X. Yang et al., "Two-Dimensional Graphene Nanoribbons," J. Am. Chem. Soc., 130 (4216) 2008.

[22] Shortly after the publication of the original Japanese version of the present article, a report on the synthesis of graphene nanoribbons from monomers on a metal surface, was published; J. Cai et al., "Atomically precise bottom-up fabrication of graphene nanoribbons," Nature 466 (2010) 470.

[23] Y. Zhang et al., "Direct observation of a widely tunable bandgap in Bilayer graphene," Nature, 459 (2009) 820.

[24] Hisao Miyazaki et al., "Bandgap Engineering of Bilayer Graphene Induced by Electric Field," the 56th Spring Meeting, 2009, 1a-ZA-3, Japan Society of Applied Physics (Japanese).

[25] N. Harada et al., "Performance Estimation of Graphene Field-Effect Transistors Using Semiclassical Monte Carlo Simulation," Appl. Phys. Exp., 1 (2008) 024002.

[26] K. Nakada et al., "Edge state in graphene ribbons: Nanometer size effect and edge shape dependence," Phys. Rev. B., 54 (1996) 17954.

[27] Y. -W. Son et al., "Energy Gaps in Graphene Nanoribbons," Phys. Rev. Lett., 97 (2006) 216803.

[28] M. Y. Han et al., " Energy Band-Gap Engineering of Graphene Nanoribbons," Phys. Rev. Lett., 98 (2007) 206805.

[29] J. Bai et al., "Graphene nanomesh," Nature Nanotech., 5 (2010) 190.

[30] R. Balog et al., "Bandgap opening in graphene induced by patterned hydrogen adsorption," Nature Mater., 9 (2010) 315.

[31] Y. Lin et al., "Operation of Graphene Transistors at Gigahertz Frequencies," Nano Lett., 9 (2009) 422.

Profile

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http://www.nistep.go.jp/index-j.html

He was engaged in technological development of the blue LED and its patent applications at a chemical company, and the development of a production-scale MOCVD system at a venture company. At present, he is with an analytical instrument manufacturer. He is interested in nanotechnology and materials because it is a basic technological field and is applied to various fields.

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6

Report on the AAAS Annual Forum (2010) on Science and Technology Policy

Yuko NAGANO
3rd Policy-Oriented Research Group

1 Introduction

An annual forum of science and technology policy sponsored by the American Association for the Advancement of Science (AAAS) was held in Washington D.C. on May 13 and 14, 2010.[1] The forum is held every year for the purpose of providing science and technology researchers with an occasion to understand and discuss such topics as policy issues facing the science community and university research institutes and budget request priorities for next fiscal year. Therefore, the forum is very helpful to understand priority issues in the U.S. science and technology policy. The forum this year, which was the 35th of its kind, was attended by more than 400 representatives from the government, Congress, universities, academic societies, think tanks and science and technology policymakers of other countries. John Holdren, President Obama's science advisor, made a keynote speech at the forum, as he did last year.

The themes of each session are as follows. In sharp contrast to last year's forum, which was filled with expectations for the newly inaugurated government of President Barack Obama, the participants in this year's forum appeared to have discussed policy issues scrupulously to examine the effects of a series of measures implemented by the government and the role to be played by science and technology amid severe fiscal and economic conditions.

[Plenary session]
・Budgetary requests for fiscal 2011[NOTE 1] and policy background
・Strengthening the U.S. climate to create innovation: Role of public policy
・National security and the role of science and technology

[Parallel session]
・Societal impacts of science and technology
・New approach to international involvement in science and technology: Trans-Atlantic outlook
・Beyond emissions trading: Different climate change problems

In this report, I would like to outline mainly the results of discussions at the sessions concerning policy trends in FY2011 R&D budget requests, innovation-related policies, and societal impacts of science and technology.

2 Keynote Speech

First, presidential advisor John Holdren introduced President Obama's views that science and technology is not merely closely related with domestic and global policy issues but is the key to the issues, that it is not only necessary to aim at practical application of science and technology but also at strengthening cross-sectional science and technology infrastructure, and that, in order to solve problems, it is necessary to establish partnerships across sectors and countries, not to mention among relevant government agencies.

Then, Holdren briefly explained the important issues that have been actively addressed by the Obama administration. Among them, Holdren first cited the fact that President Obama assigned many renowned scientists to important government posts and mentioned science and technology more frequently than his predecessors in his speeches and that the President has consistently focused attention to science and technology in budget appropriations

[NOTE 1]
The U.S. federal government's fiscal year starts in October and ends in September. For instance, the fiscal year 2011 is from October 2010 to September 2011.

since he began to take economic stimulus measures. With regard to the American Innovation Strategy (announced in September 2009), Holdren said that the strategy consists of three pillars: investment in fundamental researchers as building blocks and in STEM (science, technology, engineering and mathematics) education, efforts to promote competitive markets to create innovations, and catalyst action to break through national priority issues. He stressed that the purpose of STEM education is to raise the performance of American children in science and mathematics tests to the top in the world from the current middle level and to increase the number of college graduates to one of the largest in the world by 2020. To that end, the U.S. government has aggressively implemented various measures, including the signing of the Recovery and Reinvestment Act of 2009,[NOTE 2] and sponsored "National Lab Day",[2] a first nationwide initiative, on May 12, 2010.

In addition to these moves, Holdren introduced the government's efforts to lay down guidelines for the utilization of stem cells and rules concerning the fairness of science. He also introduced the government's recent efforts to simplify reporting procedures on the progress of federal government research grant projects.

Lastly, Holdren stated that the government has been tackling climate change issues from the perspective of alleviation, adjustment and damage. He said that the costs of action are likely to be far smaller than the cost of inaction. The government has been addressing the challenge of energy and climate change based on the recognition that it is "not energy and climate policy versus the economy" and that it is "energy and climate policy for the economy," he said.

Holdren said that the measures implemented so far include inaugurations of ARPA-E[3] and Energy Innovation Hubs,[4] establishment of carbon dioxide emission standards as the first fuel economy policy, strengthening of partnerships with China, India and other emerging countries, establishment of a task force to coordinate government agencies' response to the expansion and adoption of the U.S. Global Change Research Program,[5] and preparations of government responses to congressional deliberations on comprehensive energy- and climate-related bills.

[NOTE 2]
The Act is designed to implement large-scale economic stimulus measures, including tax cuts and various fiscal disbursements. It was enacted on February 17, 2009.

3 Federal R&D Budget for Fiscal 2011

[Distressed condition of state-run research universities]

Linda Katehi (chancellor of the University of California, Davis) reported the plight of state-run universities in California caused by severe fiscal conditions of the state government in contrast to active efforts by the federal government. She said that the situation in other states is more or less the same. She also said that the California state budget was slashed by half in the last 20 years and is expected to be further slashed by about 25% in the next 12 months. As a result, her university had to cut teachers' salaries and research expenditures. As well, she said that, 10 years ago, about 10% of the state budget had been allotted to research universities and about 6% to prisons but that the proportion has been reversed. This has forced state-run universities to raise tuitions, making it difficult to provide middle class students with high scores with an opportunity to go to college.

[Fiscal deterioration of the United States as a whole]

Douglas W. Elmendorf (Director of the Congressional Budget Office) reported that the United States is faced with fiscal deficits and an increase in government debts. In 2007, the United States ranked 15th in the world in the government debt to GDP ratio (Japan topped the list). But the country is projected to rise to a higher rank by 2020. In order to address this problem, Elmendorf stressed the need for the United States to drastically change its revenue and expenditure policies.

[Characteristics of federal R&D budget by agency and by nature]

Patrick J. Clemens (head of the AAAS research & development and policy program division) explained the outline of a total of $148.1 billion R&D budget requests (down 0.3% from fiscal 2010 budget) by agency and by nature (See Figure 1). Budget requests from many agencies increased drastically, including those from the National Ocean and Atmosphere Administration (NOAA), the National Institute for Standards and Technology (NIST), and the National Aeronautics and Space Administration. However, requests from some departments were slashed, including those from the Department of Homeland Security (DHS), the U.S. Department of Agriculture (USDA), the Department of Defense (DOD), and the Department of Transportation (DOT). Budget requests for basic research increased by 4.3%, those for development decreased 2.9%, and those for nonmilitary research as a whole increased 5.9%.

[Expanded and focused research grants by the Agriculture Department]

Roger Beachy (director of the National Institute on Food and Agriculture), while citing a sharp increase (30%) of FY2011 budget requests for subsidy programs under the Agriculture and Food Research Initiative (AFRI)[6] as a symbolic event, introduced the department's recent efforts to address social challenges, such as climate change, bioenergy, food safety, child obesity, and global food security.

4 Strengthening the U.S. Climate for Innovation

Moderator F.M. Ross Armbrecht (chairman of the AAAS Committee on Science, Engineering and Public Policy) stressed the importance of innovation and said that if the United States wants to remain a leading country in the world, it is important for the country to make long-term efforts for innovation instead of short-term efforts taking only three months ahead into view, as has often been seen in its recent fiscal policies. To that end, he called for discussions on what the United States should do now.

[NOTE 3]
Earmark refers to a portion of budget added for specific purposes during congressional budgetary debate. It is not included in the President's budget message.

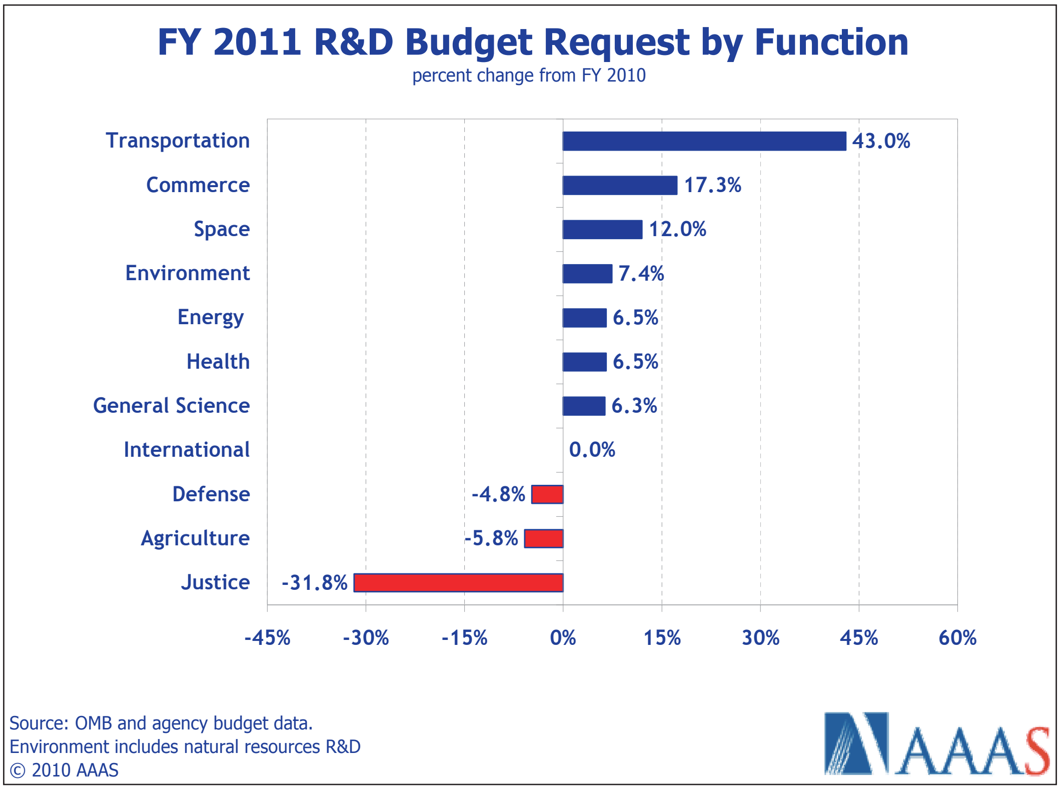

Figure 1 : Changes in FY2011 R&D Budget Requests by Government Agencies (from FY2010)

Source: Patrick J Clemens

Note: Lighter colored bars indicate percent change with projected FY2011 earmarks.[NOTE 3]

* NOAA: National Ocean and Atmosphere Administration; NIST: National Institute for Standards and Technology; NASA: National Aeronautics and Space Administration; NSF: National Science Foundation; DOE: Department of Energy; NIH: National Institute of Health; USGS: United States Geological Survey; EPA: Environmental Protection Agency; VA: Department of Veterans Affairs; DOT: Department of Transportation; DOD: Department of Defense; USDA: U.S. Department of Agriculture; DHS: Department of Homeland Security

[U.S. losing its position as "innovation leader"]

Andrew Taylor (of the Boston Consulting Group) described the situation of the United States based on the results of a survey conducted on major companies around the world. He said that the United States is now ranked 8th (Singapore ranked 1st and Japan 9th) in innovation and performance. Of the top 50 innovative companies, 23 are based in North America, 14 in Asia, 11 in Europe and one in South America. Asian companies increased from 5 in 2006 (See Figure 2). Taylor said that the United States is losing its distinction as an "innovation leader" and called on the government to make investment in R&D, education and training.

[California's own efforts to foster innovation]

Susan Hackwood, (executive director of the California Council on Science and Technology) stressed the importance of "a game changer" in innovation in order to change conventional approaches. She said that California has spearheaded innovation but that it has so far focused on such areas as communication, healthcare, international system and education system.

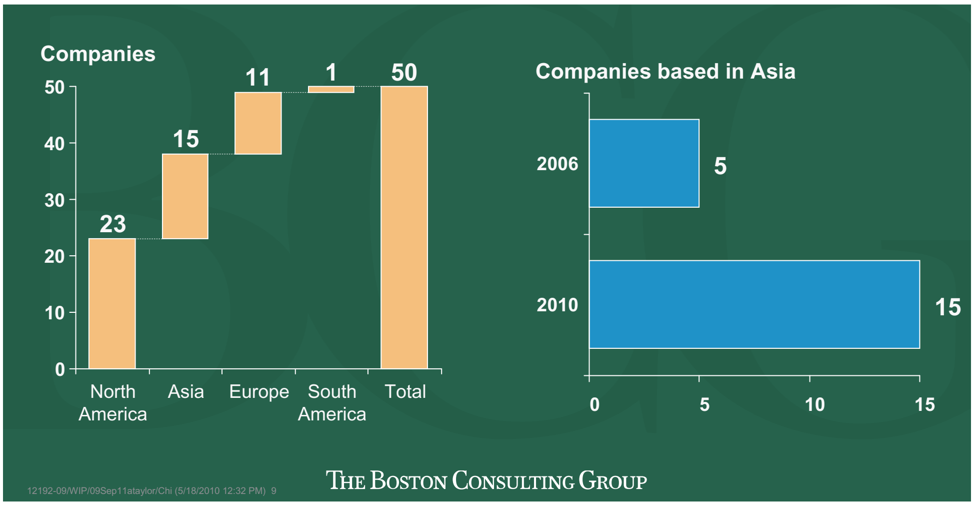

Figure 2 : Locations of 50 Most Innovative Companies (2010)

Source: Andrew Taylor

Figure 3 : Website of National Lab Day (top page)

Source: Steven Robinson

[Education initiative for innovation]

Steven Robinson (special assistant on the White House's Domestic Policy Council) described education-related projects such as "Race to the Top Fund"[7] and "Educate to Innovate"[8] campaigns under the Recovery and Reinvestment Act, which have been promoted under the initiative of President Obama in cooperation with the Department of Education. He also said that "National Lab Day," which is the latest project, is more than just a one-day event but that it is an ongoing initiative to build local community-wide networks of collaborations by actively soliciting cooperation not only from education officials and students but also from science communities and volunteers via its dedicated website (See Figure 3). Its overriding principle is "removing obstacles for students, eliminating disparities, setting goals strictly, taking a flexible approach, and promoting innovation and rewarding success."

5 Other Topics

5-1 Societal impacts of science and technology

Amid aggressive investment in science and technology by the Obama administration, it is natural that calls for the assessment of societal impacts of science and technology have increased. While efforts have been made in response to such calls, some AAAS forum attendants argued that the matter should be examined from wider perspectives.

[Structure of the Government Accountability Office (GAO) enhanced]

Timothy Persons (chief scientist at the Government Accountability Office and the science division chief at the GAO's scientific technology and engineering center) described that the GAO (which was formerly called the Governmental Accounting Office) was restructured and renamed the Government Accountability Office in 2004 and that a scientific technology and engineering center was established within the GAO in 2008 to conduct technology assessment necessary for providing independent advice[NOTE 4] to Congress on an ongoing basis. The center has conducted trend surveys and made projections of the future direction in specific areas. Persons said the center responds to requests from Congress, keeping promptness and accuracy in mind.

[NOTE 4]
The Government Accountability Office (GAO) is independent of the executive departments under law and is of equal rank with the Congressional Budget Office (CBO) and the Congressional Research Service (CRS).

[Attempt of impact evaluation of federal government's research promotion]

Stefano Bertuzzi (Office of Science Policy Analysis at the National Institutes of Health) explained the outline of STAR METRICS (Science and Technology in America's Reinvestment Measuring the EffecT of Research on Innovation, Competitiveness and Science),[9] a project which is promoted mainly by the NSF and NIH as an attempt to evaluate the scientific, economic and societal impacts of R&D projects supported by the federal government. Evaluating such impacts has come to be increasingly called for when making budget appropriations or requests under the American Recovery and Reinvestment Act. As the first stage of the project, a database necessary for the analysis of the employment situations of researchers engaged in government-funded research at six universities is being developed without imposing a heavy burden on the researchers.

In addition to these presentations, some speakers proposed to review science research priorities based on ethical standards and discipline.

5-2 National Security and the Role of Science and Technology

With regard to national security issues, which the United States has been addressing since the September 11 terrorist attacks, there are still problems challenging the country. At the AAAS forum, proposals were made and discussed to solve such problems.

[Mutual understanding of U.S. national security and higher education/science]

C.D. Mote (President of University of Maryland) spoke on the current state of the relationship between national security and universities. In the past, they were in confrontation with each other in terms of their mission and culture of higher education. However, after the 9/11 attacks, it has become necessary to understand each other and strike a balance between national security and academic freedom. In 2005, the FBI created the National Security Higher Education Advisory Board (NSHEAB), which now consists of 23 university presidents. The advisory board has promoted understanding between national security issues and higher education and discussed how they can cooperate with each other by taking up such topics as bioterrorism, cybersecurity, export control, nuclear terrorism, and visa problems. Other themes of the advisory board include internships at the FBI and scholarships from the standpoint of recruiting students as FBI officials. During a question-and-answer session, it was pointed out that researchers still have difficulty entering the United States due to the limited number of researchers allowed to enter the country, while students are allowed to enter the country on a preferential basis.

In addition to these topics, the participants also discussed a proposal from the Royal Society regarding the importance of international cooperation in nuclear nonproliferation and a report on measures and problems involved in "offensive" operations against cyber attacks.

6 Conclusion

Finally, I would like to give my impressions of the AAAS forum.

Since its inauguration in January 2009, the Obama administration has consistently paid utmost consideration to investment in science and technology, including the passage of the American Recovery and Reinvestment Act. At the same time, however, the administration and scientific circles are being urged to respond to an increased demand for the accountability for the effects of the investment. The government is also faced with a big challenge of dealing with a sharp increase in fiscal deficits, which is expected to lead to the accumulation of national debts.

It was against this background that the latest AAAS forum focused discussions on how to achieve accountability for the effects of investments made so far and for the role played by science and technology in policy and social issues and how to steer science and technology by forging solid footing. This is in contrast to last year's AAAS forum, where discussions were held in an atmosphere of expectations for Obama administration's science and technology policy.

In the United States, enhancing the quality of primary and secondary education remains a big challenge and it is positioned as a basic component in the context of creating innovation. The forum participants shared the view that it is essential for the United States to enhance the quality of education in order to secure workers with scientific knowledge and skill. Discussions at the forum revealed that the government has been making efforts, with active participation of the science community.

References

[1] AAAS annual forum on science and technology policy
http://www.whitehouse.gov/the-press-office/president-obama-launches-educate-innovate-campaign-excellence-science-technology-en
[2] "National Lab Day": http://www.nationallaboday.org/
[3] Department of Energy; Advanced Research Projects Agency-Energy (ARP-E): http://arpa-e.energy.gov/
[4] Department of Energy; Energy Innovation Hubs programs:http://www.energy.gov/hubs/
[5] United States Global Change Research Program: http://www.globalchange.gov/
[6] Department of Agriculture; Agriculture and Food Research Initiative (AFRI):
http://www.nif.usda.gov/funding/afri/afri.html
[7] Department of Education; "Race to the Top Fund" projects:
http://www2/ed/gov/programs/racetothetop/index.html
[8] White House; "Educate to innovate Campaign":
http://www.whitehouse.gov/the-press-office/president-obama-launches-educate-innovate-campaign-excellence-science-technology-en
[9] Working group of STAR METRICS projects: http://sites.nationalacademies.org/PGA/fdp/PGA_057189

Profile

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