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Synthesiology

English edition

R&D of SiC semiconductor power devices and strategy towards their practical utilization

Development of single-crystalline diamond wafers

Investigation of the distribution of elements of the whole of Japan and their applications

How car navigation systems have been put into practical use

New material development by the integration of cast technology and powder metallurgy technology

Synthesiology editorial board

2010

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MESSAGES FROM THE EDITORIAL BOARD

There has been a wide gap between science and society. The last three hundred years of the history of modern science indicates to us that many research results disappeared or took a long time to become useful to society. Due to the difficulties of bridging this gap, it has been recently called the valley of death or the nightmare stage (Note 1). Rather than passively waiting, therefore, researchers and engineers who understand the potential of the research should be active.

To bridge the gap, technology integration (i.e. *Type 2 Basic Research* – Note 2) of scientific findings for utilizing them in society, in addition to analytical research, has been one of the wheels of progress (i.e. *Full Research* – Note 3). Traditional journals, have been collecting much analytical type knowledge that is factual knowledge and establishing many scientific disciplines (i.e. *Type 1 Basic Research* – Note 4). Technology integration research activities, on the other hand, have been kept as personal know-how. They have not been formalized as universal knowledge of what ought to be done.

As there must be common theories, principles, and practices in the methodologies of technology integration, we regard it as basic research. This is the reason why we have decided to publish "*Synthesiology*", a new academic journal. *Synthesiology* is a coined word combining "synthesis" and "ology". Synthesis which has its origin in Greek means integration. Ology is a suffix attached to scientific disciplines.

Each paper in this journal will present scenarios selected for their societal value, identify elemental knowledge and/or technologies to be integrated, and describe the procedures and processes to achieve this goal. Through the publishing of papers in this journal, researchers and engineers can enhance the transformation of scientific outputs into the societal prosperity and make technical contributions to sustainable development. Efforts such as this will serve to increase the significance of research activities to society.

We look forward to your active contributions of papers on technology integration to the journal.

Addendum to Synthesiology-English edition,

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Synthesiology Editorial Board

Note 1 : The period was named "nightmare stage" by Hiroyuki Yoshikawa, President of AIST, and historical scientist Joseph Hatvany. The "valley of death" was by Vernon Ehlers in 1998 when he was Vice Chairman of US Congress, Science and Technology Committee. Lewis Branscomb, Professor emeritus of Harvard University, called this gap as "Darwinian sea" where natural selection takes place.

Note 2 : *Type 2 Basic Research*
This is a research type where various known and new knowledge is combined and integrated in order to achieve the specific goal that has social value. It also includes research activities that develop common theories or principles in technology integration.

Note 3 : *Full Research*
This is a research type where the theme is placed within the scenario toward the future society, and where framework is developed in which researchers from wide range of research fields can participate in studying actual issues. This research is done continuously and concurrently from *Type 1 Basic Research* (Note 4) to *Product Realization Research* (Note 5), centered by *Type 2 Basic Research* (Note 2).

Note 4 : *Type 1 Basic Research*
This is an analytical research type where unknown phenomena are analyzed, by observation, experimentation, and theoretical calculation, to establish universal principles and theories.

Note 5 : *Product Realization Research*
This is a research where the results and knowledge from *Type 1 Basic Research* and *Type 2 Basic Research* are applied to embody use of a new technology in the society.

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Contents

R&D of SiC semiconductor power devices and strategy towards their practical utilization

— The role of AIST in developing new semiconductor devices —

Kazuo Arai

[Translation from *Synthesiology*, Vol.3, No.4, p.259-271 (2010)]

The realization of SiC semiconductor power devices has been highly expected to contribute to energy saving, however, it requires overcoming various technological barriers. AIST has been contributing to this objective for more than 15 years mainly through participation in national projects. Corresponding to the changes of organization of the institute, in this paper, R&D activities for the past years are described in three parts, i.e., 1) the R&D targets, 2) the major issues and strategies for overcoming them and the main results, 3) the evaluation of the validity of the strategies, and lastly, future issues are suggested.

***Keywords* :** Silicon carbide, wide-gap semiconductor, wafer technology, power semiconductor device, power electronics

1 Introduction

At the 15 institutes under the former Agency of Industrial Science and Technology that was the precursor of the current National Institute of Advanced Industrial Science and Technology (AIST) in the 1990s, majority of the researchers were material researchers. In the long-term material research, how we can present our importance to society was a subject of frequent discussions. In the late 1980s, the United States was experiencing economic slowdown, and the American basic researchers were visiting Japan to sell their research. The Japanese national research institutes at the time were in the phase of “shift to basics” or putting emphasis on leading-edge basic research. Some material researchers armed with their specialties engaged in the study of whatever material that was in vogue at the time. At the Electrotechnical Laboratory (ETL), a consciousness shift was promoted under the concept “material is useful only when it is used”. The ETL was being left behind in the state-of-art technological development of silicon LSI, but was starting a series of pioneering R&D in the field of materials. It was concluded that to study the material group with prospects for practical utilization in future electronic devices, emphasis should be placed on the wide-bandgap semiconductors such as silicon carbide (SiC) as well as gallium nitride (GaN) and diamond that were expected to achieve low-loss high-frequency operation and high-temperature high-radiation resistance (Fig. 1).

In this paper, the development of the SiC semiconductor power device and the activities toward its practical utilization will be explained in terms of 1) the research goal, 2) the individual issues and strategies for solutions and the results, and 3) the evaluation of the adequacy of the strategy, in relation to the changes in the changes in the organization of AIST. Finally, the future issues will be discussed[Note 1] (Table 1).

2 Goals of R&D at various periods

2.1 Position of R&D in the whole picture

Recently in Japan, the energy issue in 2100 was discussed in terms of the limited resources and environment, and the direction of the technological development was laid out to deal with the issue[1]. It is estimated that sustainable development will be possible only through thorough energy saving by using electric power that is superior in efficiency, convenience, and economy, and such power is attainable by the massive introduction of renewable energy and nuclear power. Needless to say, power electronics will become important as the common basic technology that will be the key to the effective use of electric power. The key technology of power electronics is power device. While the researchers try to increase performance by improving the design of the structure of the current silicon semiconductor power device, it is approaching the theoretical limit calculated from the physical parameters of silicon. The major performance index of a power device is how low the loss is. To achieve the low-loss property, the low on-resistance (where the resistance during current conducting is low) and high switching speed are required. In the SiC wide-bandgap semiconductor that has a band gap about three times greater than silicon, the dielectric breakdown field is about one digit greater than silicon, and the theoretical limit of the on-resistance is less by two digits. In silicon, a power device with low on-resistance yet with low switching speed (IGBT) has been developed, although its application is limited. The SiC power device that allows low on-resistance and high-speed

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Table 1 Flow of the activities

Organization	Material Science Dept., ETL (1993~2001.3)	Power Electronics Research Center, AIST (2001.4~2008.3)	Energy Semiconductor Electronics Research Laboratory, AIST (2008.4~)
Main activity	· Survey (FY 1994~1995) and leading research (hard electronics) (FY 1996~1997)	· Development of Basic Technology for Ultralow Loss Power Device (FY 1998~2002) · 2 topics in open proposal for energy saving (FY 2003~2005) · 3 topics subcontracted to AIST (module, power supply, system) (FY 2002, 2004, 2003~2006 respectively) · "Development of Basic Technology for Power Electronics Inverter" (FY 2006~2008)	· Industrial Transformation Research Initiative (manufacturing line for SiC device prototype) (FY 2008~2011) · Development of Basic Technology for Future Power Electronics (FY 2009~2012)
Goal	· Clarification of goal →Power device	· Total solution strategy (concurrent development of wafer – device – equipment)	· Concurrent development of demonstration, core, and pioneering researches
Main result	· NEDO project starts	· Construction of SiC basic technology in Japan · Clarification of possibility of SiC power devices and equipment (wafer quality, low-loss and reliability of devices, increased power density of equipment) · Establishment of wafer venture (LLP)	· Demonstration of application to equipment (joint research with industries)
Notes		· Concurrent development of GaN devices · Participation of experienced people from industries · Construction of device fabrication line	· International exchange and collaboration

switching in wide blocking voltage range (MOS-FET and junction FET) will alleviate the limitations of the silicon power device. The power loss during device operation can be reduced by low on-resistance and high-speed switching, and with the downsizing and simplification of the heat dissipation structure (heat release fin or fan) as well as downsizing of the passive components through use of high-frequency, significant cost reduction can be expected for power electronics equipment such as inverters, and this will eventually lead to energy saving. The increased power density (or the downsizing) of the electric power converter is an important index in introducing the converter to society, and has been indicated in the roadmap (Fig. 2). In addition, the high blocking voltage, high-temperature operation, and high breakdown resistance of the SiC power device are expected to allow pioneering new fields of power electronics application. To "achieve the ubiquitous power electronics" that support thorough energy saving, the practical utilization of the SiC device is expected to play an extremely important role.

2.2 Goals during the ETL period (1993~2000)

Material research should not stop at the search in the style of the material science, but should aim for the practical utilization by clarifying the principle superiority through creation of actual devices in a wide sense. The potential of SiC, GaN, and diamond as devices were carefully reviewed, and the research subjects and the goals were narrowed down. The goal was set "to show that SiC possessed principle superiority in the power device application against current silicon in the wide band gap semiconductors, and also to show that SiC has a leading edge compared to other wide

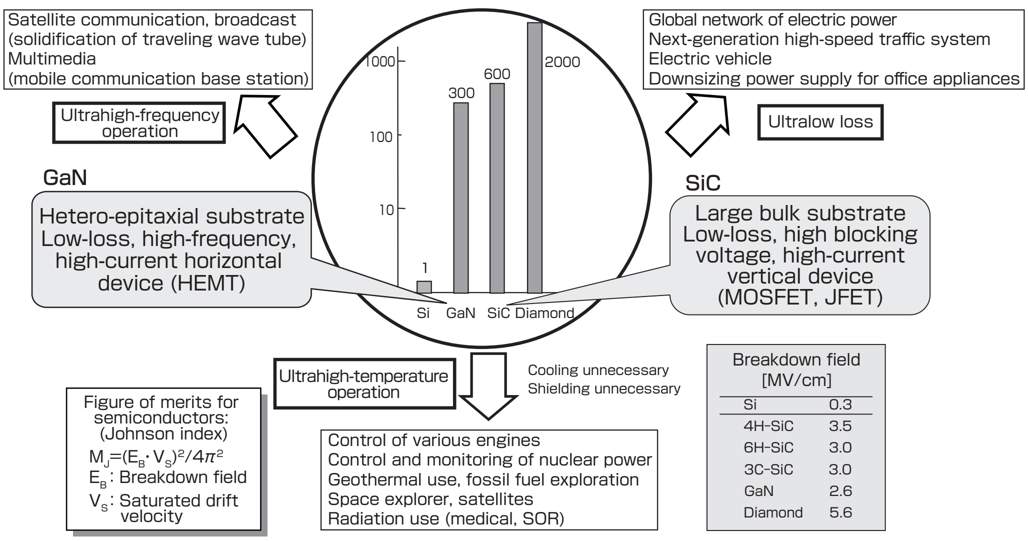


Fig. 1 Hard electronics (the world of wide-bandgap semiconductors)
In the wide bandgap semiconductor, the dielectric breakdown field is large and the saturated mobility rate is also large. Therefore, the figure of merits of the semiconductor is one digit greater compared to the silicon semiconductor devices. The on-loss (current-conducting loss) of the SiC power device is estimated to be 1/200 of the Si device.

band gap semiconductors in practical application".

2.3 Goals during the AIST period (2001~2007)

The ETL was reorganized as AIST, just when ETL was playing its role in the concentrated research for the "Development of Ultralow Loss Power Device Technology" (FY 1998~2002), a project of the New Energy and Industrial Technology Development Organization (NEDO). Through the discussions with the researchers of the power electronics application in the "Next-Generation Power Semiconductor Realization Commission" conducted under the project, we became aware that "although the power device may be the key to power electronics, collaborative development along with the development of converters and system application is mandatory in order to realize the power device". Proposal was made to establish the Power Electronics Research Center (PERC) that engaged in the integrated R&D from material and device development to converter and system application. This was approved. The goal of this research center was "to clarify the contribution to the ubiquitous power electronics (that is the innovation in power electronics) by increasing the performance of the SiC power device and to gain prospect for its system application".

2.4 Goals of the AIST period (2008~)

As the activities at PERC was recognized and the decision was made "to act in unison as a R&D group to take the next step" at AIST, the Energy Semiconductor Electronics Research Laboratory (ESERL) was established to follow PERC in 2008. The next goal was "to continue the integrated effort of wafer and material technology, device technology, and systemization technology, and to generate innovations in power electronics by accelerating the practical utilization and diffusion of the SiC power devices".

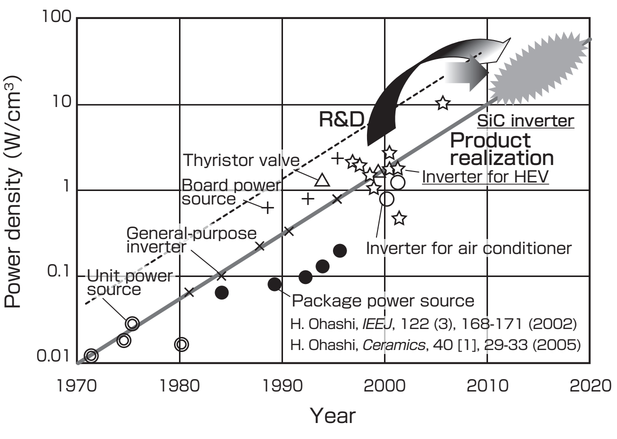


Fig. 2 Roadmap of power converter seen in terms of power density

There has been a double-digit increase in the last 30 years. While the efficiency of the converter is becoming saturated, the increase of power density will lower the cost of the converter, and this will be a major point for the diffusion. The demonstration of R&D sample is necessary 10 years ahead of the product realization (R&D line).

3 Issues extracted, strategies to solve the issues, and the results during each period

3.1 Strategies and results of the ETL period - Construction of the foundation of the SiC power device development in Japan -

At ETL, a pioneering R&D was conducted where the 3C-SiC (cubic crystal), which was the low-temperature polymorphism of the SiC crystal, was hetero-epitaxially grown on the silicon wafer and the prototype diodes and transistors were fabricated to demonstrate the device property[2]. The SiC device R&D projects supported by the government in the 1980s were started together with the "superlattice device" project and "3D circuit device" project under the "R&D Program on Basic Technologies for Future Industries". However, as the main goal was the environment (heat and radiation) resistant devices (mainly GaAS devices), the industries felt very little attraction and the projects were continued with minor effort. In the beginning of the 1990s, the 30 mm diameter SiC monocrystal (hexagonal crystal) became commercially available in the United States, and the expectations for SiC in the power device began to rise.

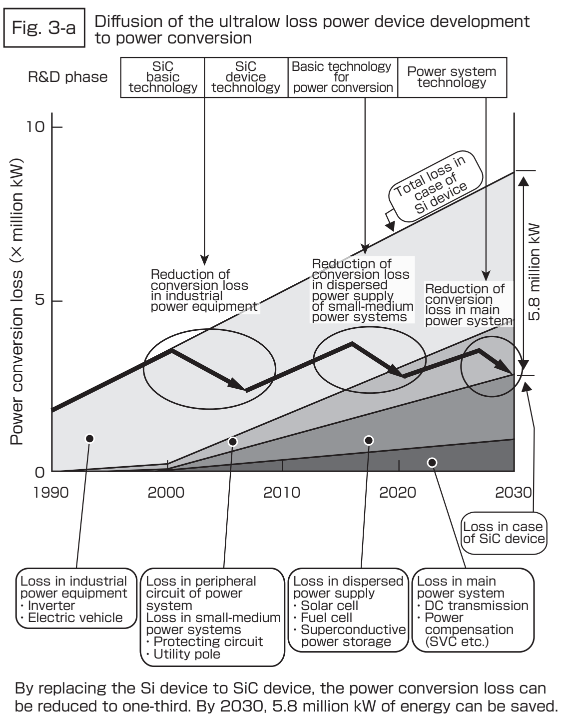
3.1.1 Narrowing down to SiC for use in power device and concentrated research method

In the United States, the R&Ds for SiC and diamond as the electronic devices for military application became active under the support of the US Defense Advanced Research Projects Agency (DARPA). In Japan, it was necessary to clarify the positioning of the wide-bandgap semiconductor R&D for the purpose of industrial application. In 1994, the survey of the necessary fields and the available technology was started under the Japan Electronics Industry Development Association (JEIDA). It was proposed that the wide-gap semiconductor SiC, GaN, and diamond would be the semiconductor materials that may enable a device that was resistant to extreme conditions such as high-power, high frequency, and extremely severe environments. It may pioneer a new electronic field called "hard electronics"[3] (Fig. 1). After two years of NEDO leading research "Hard Electronics" (FY 1996~1997), the goal was narrowed down to the development of the basic technology for the low-loss power device that might have great impact on industry, focusing on SiC for which the commercial sale of two-inch wafers was started. The five-year NEDO project "Development of Ultralow Loss Power Device Technology" (FY 1998~2002) was started in 1998 (NEDO and Research and Development Association for Future Electron Devices (FED)). The project was powered not only by the statement, "Although this R&D is conducted for military application in the United States, the basic research that has potential of blooming as an industry should be supported by the Ministry of International Trade and Industry (the present Ministry of Economy Trade and Industry (METI))", but also by emphasizing that a great energy saving can be expected by introducing the SiC power device, and a new device industry using the SiC semiconductor would rise (Fig. 3).

In the “Development of Ultralow Loss Power Device Technology” project, it was necessary to quickly build the wafer technology and the device process technology that would serve as the foundation of the power device development in Japan, which at the time was mostly basic research. Therefore, the Schottky diode for which practical devices have been developed was not set as the main subject, but the development was narrowed to the basic technology for the switching device that might bring about innovation in power electronics. In this project, the three device manufacturers that were capable of fabricating the FET device -- Hitachi, Ltd., Mitsubishi Electric Corporation, and New Japan Radio Co., Ltd. -- developed the prototypes for different types of FET (MOSFET, JFET, and MESFET) in their laboratories. Concurrently, this was a project in which the integrated basic R&D of material, process, and device was conducted by the industry-government-academia at AIST. This was a concentrated research method where the participating researchers would convene in one place, as a joint R&D with the R&D Association for Future Electronic Devices (Fig. 4). The mixed groups of industry-academia-government were formed for each main elemental technology to engage in the technological development of the SiC semiconductor, since it required different elemental technologies from those for Si semiconductors. This project helped build the foundation of the SiC power device R&D in Japan, along with the NEDO Important Regional Technology Development “Development of Control System Technology for Combustion to Rationalize Energy Use” (FY 1994~1999) that was conducted in the Kansai region for six years from 1994, led by Professor Hiroyuki Matsunami of the Kyoto University (currently director of Campus Plaza Kyoto). In May 2000, an international workshop was held to announce the national SiC R&D to the world[Note 2]. This was effective in obtaining international cooperation in the field where there were very few researchers. The development approaches and results that were unique to this project will be described in the next section.

3.1.2 Results of the “R&D of Ultralow Loss Power Device Technology” project

At the time, the SiC wafer was supplied almost exclusively by Cree, Inc. of the United States. When a device manufacturer wishes to invest safety in the product realization of a device, it is necessary to have a second source that can provide a stable supply of the wafers. With the exclusivity of supply, there was concern for the stability of the supply, and as the price and the quality of the wafer depended on one company only, the device company will have less say in the wafers that are linked directly to the cost reduction and performance increase of the device. Therefore, under the concentrated



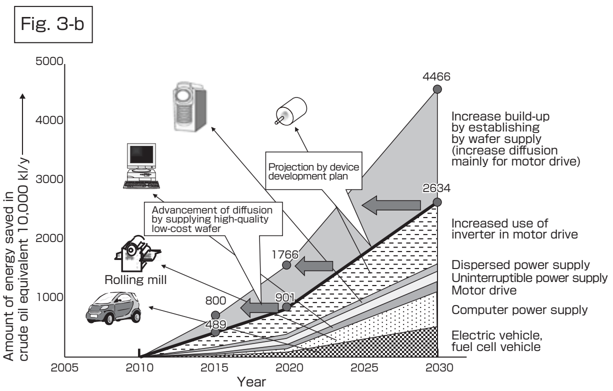


Fig. 3 Effect on energy saving when the SiC device is implemented in Japan

The original figure was published in *Kogyo Gijutsu* (H. Ishii, Aug 1997) (Fig. 3-a). After several revisions, it was used in the *Strategy for Energy Saving Technology* (Fig. 3-b).

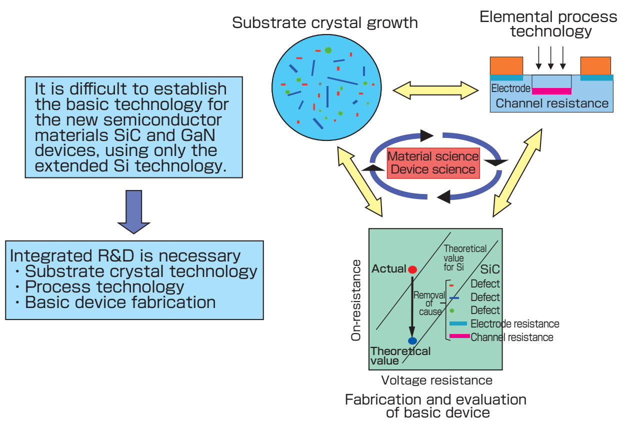


Fig. 4 Development concept of the NEDO project “Development of Basic Technology for Ultralow Loss Power Device”

research method, the project formed a group consisting of ETL and two companies (Showa Denko K.K. and Denso Corporation; later joined by Nippon Steel Corporation) that have started the growth of SiC monocrystals. The approaches selected for this R&D were the on-site observation of x-ray topography of the crystal growth process and the in-furnace visualization by simulation (Fig. 5)[Note 3]. In fabricating the device, a micron-order hole accompanied by screw dislocation in the wafer (micropipe) would be fatal. Therefore, the objectives of the project were the fabrication of a two-inch substrate without micropipes and the growth of crystals with external diameter of four inches. An important technological contribution was the scientific presentation of the crystal growth technology that was a corporate know-how that had not been disclosed until then at academic societies. After the completion of the project, the developed technology was transferred to several Japanese companies that wished to manufacture the crystals.

In high blocking voltage and high-power vertical power device, the low resistance is achieved by introducing impurities at high concentration (the n-type semiconductor is normally achieved by nitrogen doping) to the substrate crystal. Therefore, to realize the desired device characteristics, the homo-epitaxial monocrystal film growth technology is important where the film is formed on the SiC monocrystal by carefully controlling the film thickness and the impurities concentration. The group led by Professor Matsunami of Kyoto University developed a step-controlled epitaxy where high quality growth could be achieved at relatively low temperature (~1600 °C) by introducing the off-angle surface. The project introduced an overseas epitaxial growth system with established performance, and the necessary epitaxial film was supplied to the device fabrication group after fine-tuning the growth conditions. On the other hand, a new high-speed epitaxial device was developed (few years later, this achieved a growth rate of over 100 μm/h on a three-inch substrate). Near the completion of the project, in addition to the silicon face that was the crystal-forming surface of the device thus far, the epitaxial film growth technology that allowed control of the impurities in the carbon face, which is the other side of the silicon face, was developed. It was demonstrated that the channel mobility of the MOSFET was almost one digit greater compared to the silicon face, and the basic device patent was obtained for the carbon face device (Fig. 6). At present, there are still issues that must be resolved in the carbon face device process, but it is developing into a main technology toward practical utilization.

Although the advantage of SiC is that a SiO_2 insulating layer can be formed by thermal oxidation, the channel mobility of the MOSFET obtained by oxidation is extremely low compared to the bulk (in normal thermal oxidation, it is two digits less than the mobility of bulk). The thermal diffusion of impurities that worked extremely well in the silicon process could not be used in the SiC process, and the high-temperature ion injection followed by the high-temperature activation process was necessary. The development of low resistance contact formation technology had to be done quickly. Also, the device parameters necessary for the device design were uncertain or unavailable. These issues were handled systematically in the concentrated research method. For the necessary physical property and process evaluations, we asked the cooperation of universities and external organizations. These results helped build the foundation of this field in Japan that was behind in the device technology development, as well as demonstrated the performance of the prototype SiC power device that surpassed the performance of silicon created by the dispersed research method.

Another important characteristic of this project was that it was conducted under the Engineering Advancement Association of Japan (ENAA), an organization that emphasized the R&D of system application of the practical utilization research (NEDO project "Development of

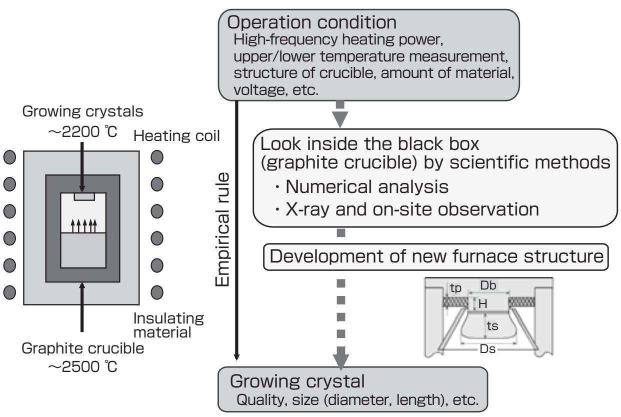


Fig. 5 Approach for the development of SiC monocrystal growth technology
The structure inside the furnace was almost never disclosed at the academic societies or any other places.

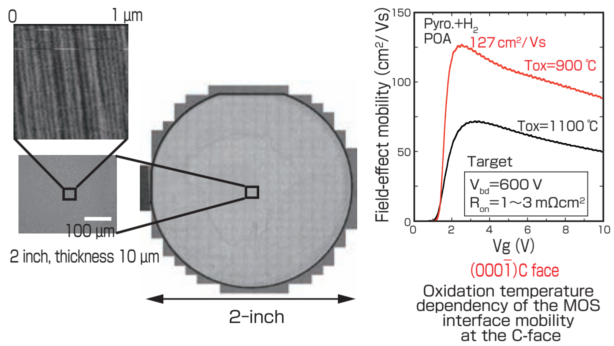


Fig. 6 Development of the carbon-face device technology
The development of the epitaxial growth technology on the carbon face (C-face) and the channel mobility of MOS fabricated on the face (Morphology of the epitaxial surface (the water-like smudges are image artifact)).

Ultralow Loss Power Device Technology: Practical use survey of the future power semiconductor device", FY1998~2002, ENAA). This activity promoted the exchange between the basic research and application fields, and we were able to make prospects that SiC was superior in principle against silicon in the industrial application of the power devices.

To widely spread these results, these results were comprehensively described in a book[4].

3.2 Strategies and results of AIST period (2001~2007) - Proposal of a total solution from wafers to a system -

There were two years left of the NEDO project, and a structural organization from the Agency of Industrial Science and Technology to the National Institute of Advanced Industrial Science and Technology occurred in 2001. In this reorganization, the research centers were designed as units with specific missions. In this R&D phase, we were beginning to see the prospects of the SiC power device. Whether the new device would be practically utilized in power electronics depended not only on the performance of the device, but it was clear that we needed to optimally integrate the various elemental technologies that tended to be at trade-off with each other (Fig. 7). During this period, R&D of power electronics in Japanese industry was difficult due to the reduced investment in infrastructure. For R&D for the practical utilization of the new power semiconductor device, the role of the public institution was important in the long-term R&D. With this thinking, we conducted an integrated basic R&D (total solution) in one research unit that included everything from material and device process development to converter and system application. We declared the realization of "the innovation of power electronics through innovative power device", and established PERC composed of five groups.

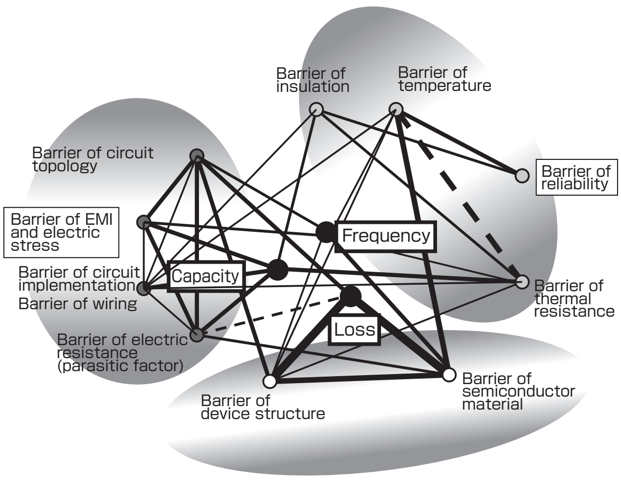


Fig. 7 Various issues of the power module technology

The various elemental issues are complexly interrelated, and must be solved concurrently (created by Ichiro Omura, Toshiba Corporation, Next-Generation Power Semiconductor Device Commission).

During the first half period of PERC, the effort was spent on achieving the goal of the "Ultralow Loss Power Device" project. This was incorporated into the goal of "the innovation of power electronics through innovative power device", and the activities commenced fully. There were 14 full-time staff members, while there was no full-time staff in the Circuit and Implementation Team, and the researchers from other research units in AIST concurrently worked for the Implementation and System Application Teams. At the commencement, from the perspective of selection and concentration, there were questions raised about such an integrated approach. However, it was gradually accepted since one of the central tenets was the promotion of "*Full Research* based on *Type 2 Basic Research*" as declared by AIST. The staff was increased to 18 people in 2007, and combined with the full-time members and the five dual-duty researchers, there were over 80 people involved.

When the "Ultralow Loss Power Device" project was completed, the R&D at AIST was continued as two topics of the NEDO open proposal for Energy Saving (FY 2003~2005), "Basic Research for Ultralow Loss Device, MOS Reliability and High Power Densification of Converter" and "Development of Advanced Diode", jointly proposed with the corporations for further practical utilization. As a result, it continued on to the NEDO project "Basic Technology for the Power Electronics Inverter (or the "Inverter" project)" (FY 2005~2007). There, the demonstration of the converter was conducted with Mitsubishi Electric Corporation. R&Ds for the current capacity increase, high reliability (MOS oxidation film) to warrant the realization of the power device, and R&D to seek potential of high power densification of the converter were conducted with the corporations through the concentrated research method.

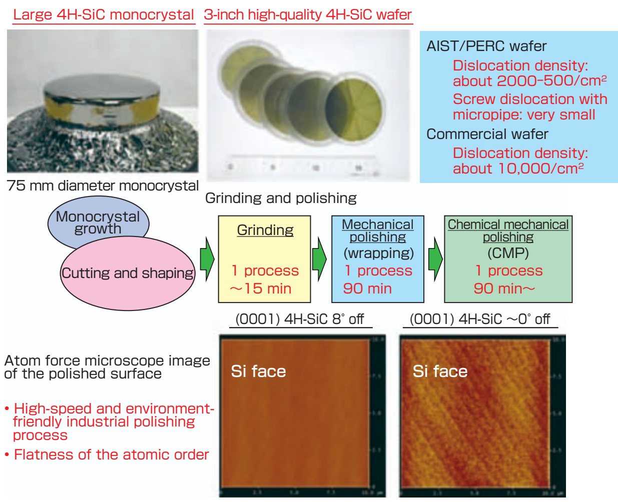


Fig. 8 Fabrication technology of SiC monocrystal wafer

Increasing the quality and decreasing the cost of wafer are the primary issues in the practical utilization of the SiC power device. For decreasing the cost, the development of peripheral technologies such as monocrystal cutting and polishing is also important.

3.2.1 Contribution to the wafer issue

The technologies developed in the project were published at the academic societies, and were actively transferred to industry. Considering the repeated A-face growth (RAF) method developed in Japan, developments were conducted to reduce the crystal defects and to increase the diameter. Also, the cutting and polishing technologies essential for the fabrication of the wafer and the technological transfer were conducted (Fig. 8). In epitaxy, it was found that the growth was possible in the off-less face on the C-face, and the mobility at the MOS interface formed on the C-face was high. To promote the practical use of the epitaxial technology based on these findings, a joint research system was formed by the Central Research Institute of Electric Power Industry, Showa Denko K.K., and AIST. A limited liability partnership (LLP) called the ESICAT Japan, was established based on this research to construct the epitaxial wafer supply system that was the rate-controlling factor of the R&D (that is the controlling factor of the turn around time of device fabrication), and to utilize these wafers in the "Inverter" project. This activity was turned over to Showa Denko in 2007.

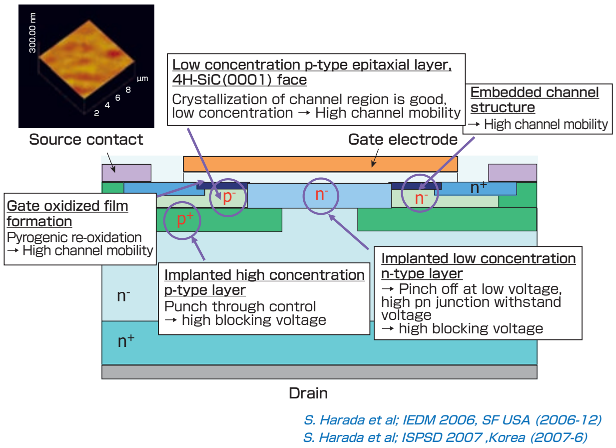


Fig. 9 Device structure of the IEMOSFET (implantation and epitaxial MOSFET) fabricated on the carbon face and its effectiveness

The surface on which the channel is formed is flattened using the epitaxial growth technology and the ion injection technology (AFM image), to improve the channel mobility.

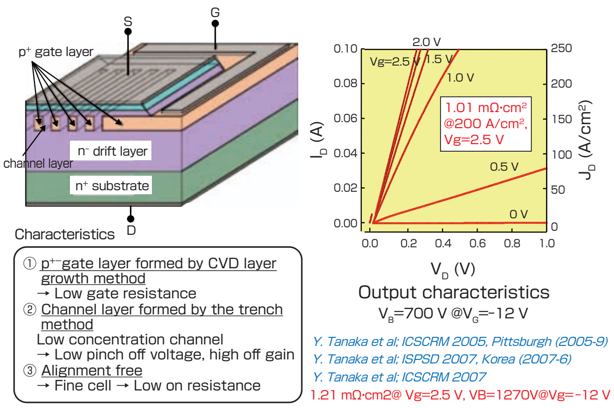


Fig. 10 Structure of buried gate type SIT and its static property

Although it is normally on (it will not turnoff unless gate voltage is applied), the current-conducting loss is extremely low. The epitaxial growth technology also plays an important part in this device.

3.2.2 From principle demonstration of the power device to converter

For the switching device, the development of the junction FET (JFET) was conducted. Although the ampere class device was available on the market, it has not been widely used since it was a normally-on device (a device that is switched on at zero gate voltage). MOSFET has not been marketed since the MOS channel mobility can not be increased and the reliability of the oxidation layer is unclear. AIST developed the Implantation and Epitaxial MOSFET (IEMOS) by utilizing the epitaxial process of MOS channel by employing the high channel mobility of the carbon side, and succeeded in the principle demonstration of a device with world lowest loss. For JFET, using the imbedded gate structure (static induction transistor (SIT)) made by the epitaxial technology, we succeeded in the principle demonstration of low on-resistance to the level where further reduction of the substrate resistance would require further performance improvement (Figs. 9, 10 and 11). The device process technologies became intellectual properties, and were technologically transferred to industry as needed.

For IEMOS, the prototype of the ampere class ultralow loss device was fabricated and supplied in the "Inverter" project.

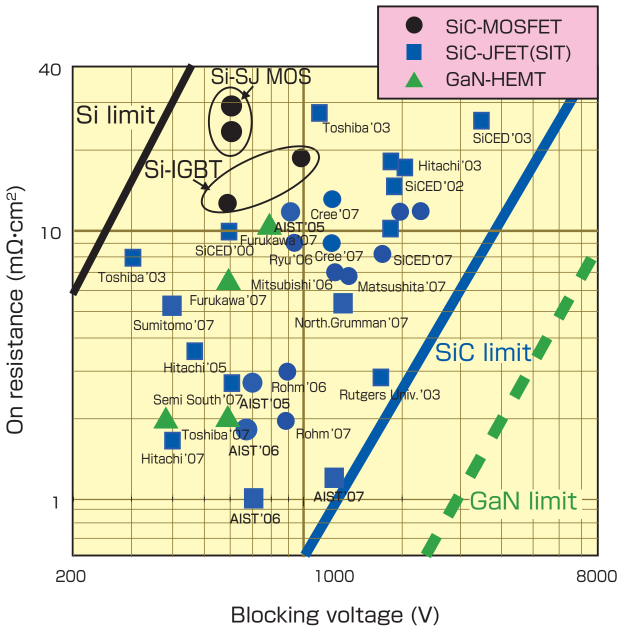


Fig. 11 Trends in the on resistance and blocking voltage of the ampere class switch

AIST has yielded top results in the world. For the recent trends in the Si devices of IGBT and J-MOS as well as the trends of the SiC power devices in the world, refer to "Technological innovation and application of power electronics taken to the next step" by Kazuo Arai in *Ohm* November 2009 issue in Japanese.

By the end of the project, the conditions for realizing the high power density converter of 50 W/cm^3 were clarified. To set the milestone of the technological development at the research center, we utilized the "High-Tech Manufacturing" Research Program established by AIST to promote the manufacturing technology in 2006. There, the crystal substrate, epitaxial film, IEMOS and Schottky barrier diode device, and chopper circuit were fabricated jointly with the three research teams, to achieve the control of the generator motor and to verify the total solution (Fig. 12). For the JFET (SIT) and PIN diodes, there were no concern about the reliability of the gate oxide, and the fabrication technology was developed and obtained a yield that allowed the device to be supplied for the converter. The joint research for system application was started with the corporation around 2007, and the results have been obtained starting in 2008.

3.2.3 Increased current capacity and reliability of the device and the wafer quality

For the demonstration of the power device for its practical utilization, device chips of over 10 A to 100 A were required. At the point of 2005, reports of increased current capacity were starting to be heard for the Schottky barrier diode, while the development was delayed in the switching device. The quality of the wafer (such as crystal defect) was considered to be the major cause. Considering the result of the leading research for energy saving, the "Inverter" project set the goal of clarifying the wafer quality to achieve the high-capacity chip of 100 A class. In reality, the monocrystal substrate had about 10,000 /cm^2 of crystal defects (dislocations). Therefore we worked to clarify the relationship with the crystal defects and the reliability of MOS and increased device capacity that was not studied seriously until then. The crystal defect evaluation using the synchrotron radiation light was deployed at AIST. We obtained the conclusion that while certain degree of reduction in crystal defects was desirable, we could go ahead with the current crystal quality through the advancement of growth technology of the epitaxial film formed on the crystal substrate for fabricating the device (minimization of the surface defect during epitaxial growth,

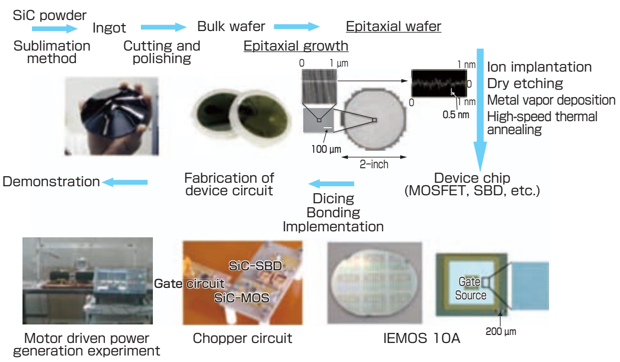


Fig. 12 Demonstration of the total solution by all PERC technology (wafer – device – converter) in the "High-Tech Manufacturing" Project (see text)

conversion of the crystal defect type, etc.), and work on the device process (gate oxidation layer formation where both channel mobility and reliability are obtained, high-temperature ion implantation and post activation process, etc.).

3.2.4 Construction of the converter design method and application to high power densification

The conditions and environments in which the power electronics devices are used are varied, and optimizations were obtained by trial-and-error in the past developments. The desired performances of the devices differ according to the use. Particularly, the SiC power device is used for high-speed switching under the condition of high current and high blocking voltage, and the integrated design of device circuit, passive components, and converter structure to maximize the device performance is also important (Fig. 13). For example, at higher frequency, the effects of floating capacitance and floating reactance that did not have to be considered before manifest, and their evaluation and reduction become necessary. AIST developed the circuit integration design composed of device simulation, filter performance, control method, and others, and developed the "simulator for converter loss integrated design" in the "Inverter" project. Combined with the prototype evaluation of the low-loss SiC-MOSFET, we clarified the condition for the high power density of 50 W/cm^3.

3.3 Strategies and results of AIST period (2008~) - Resolving the bottleneck to the practical utilization -

After 2008 at AIST, the wafer, device, and converter that completed the principle demonstration advanced to the downstream demonstration research, and this flow is an important approach for the practical utilization of SiC. During this period, AIST set as its goal the basic research with higher goal needed for the R&D that spiraled upward,

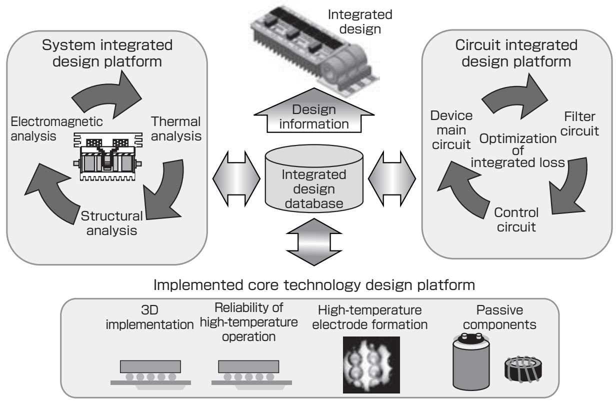


Fig. 13 Conceptual diagram of the integrated design for power converter

The integrated loss of device – filter (magnet) – control is simulated. This will enable optimization of the loss in the circuit design. The integrated loss design simulation of the converter becomes possible by integrating the database of the passive components and the structural factors.

and to engage in pioneering research that may contribute to further developments in this field.

With the demonstration of the 70 % loss reduction for the 14-kVA inverter by a company in the “Inverter” project and the potential for the device application at the current crystal quality through the concentrated research method, the “Basic R&D for Future Power Electronics” (FY 2008~2011) started within the framework of the Green IT project from FY 2008. There, the demonstration of power electronics device with clear application was conducted by Hitachi Ltd. and Mitsubishi Electric Corporation, as well as the basic technology development aiming for the high power density (development of the ultralow loss device and demonstration of the prototype for the high power density converter) through the third concentrated research at AIST.

In the development of the wafer technology, the development of the four-inch wafer was accomplished in Japan in the end of 2007, and this accelerated the practical utilization. In the sublimation crystal, issues remain in increasing the diameter (six inch or more) to reduce the cost of the device, as well as other cost issues such as the productivity of cutting and polishing technologies. The epitaxial technology plays an important role in the formation of the device structure, and the diffusion of high-quality epitaxial technology is also important. Moreover, it is necessary to pursue the new growth technology to replace the sublimation method to increase the crystal quality, and we are starting activities to address those issues.

SiC power electronics was undergoing an evolution in the wafer and device developments, and the interest in its practical utilization was rising. However, for the wafer industry, the demand projection was unclear, and industry was hesitant to make any large-scale investments. For the device industry, the market projection considering the quality and cost of the wafer was unclear, and it was difficult to make a decision for full production. Also, for the companies involved in system application, the device was not readily available. The situation was a so-called “three-party deadlock”. It was necessary to provide support so this relationship would turn into positive feedback for each other. The technological support for the wafer industry, where the expensive epitaxial growth device was the bottleneck for commercialization, came in the form of ESICAT Japan, LLP.

At AIST, the “Industrial Transformation Research Initiative”, the large-scale collaborative project of industry-academia-government, was conducted for several topics. From the end of the FY 2008, the Industrial Transformation Research Initiative “Mass Production of SiC Device Prototype and System Application Demonstration” started its three-year course. Through the collaboration with a device company, Fuji Electric Holdings Co., Ltd., we aim for a practical production technology for the device chip, to quickly supply the device chips to the companies and universities that are attempting system application to the converter, and to clarify the potential of the application field.

4 Evaluation of the strategy

4.1 ETL Period

4.1.1 Narrowing down the development target to SiC power device

Through the exchange with the people in charge of surveys and policymaking, the target of “Hard Electronics” was narrowed down to the SiC semiconductor, where the wafer development was already being done to create the power device. We were able to clarify the vision of creating a new industry and the contribution to energy saving. Through long-term survey, the system for a national project became possible. Flexible responses were made to accommodate industry, and the dispersed research method (involving three companies) for the device development and the concentrated research method that aimed for the construction of basic technology functioned effectively. These were extremely useful for the development of this field later.

4.1.2 Space for the start-up of R&D and procurement of human resources

At ETL, the project started as a group of participants and post docs within the institute mainly among the material and property researchers. In the concentrated research method, the role played by the participants of the companies was large, along with the use of the corporate facilities. The material and property researchers employed as post docs were encouraged to grow into people who could take charge of the device process, and they would eventually engage in prototype production of simple devices. Care was taken in the management, such as holding frequent meetings to raise the morale and research potential. The procurement of space needed for the facility was extremely difficult. If there were appropriate space, we would have moved, but the burden of moving was too great on the staff, and we became painfully aware of the importance of infrastructure in device development. At the beginning of the project, some thought that we could stay at crystal growth and epitaxial growth in the concentrated R&D method. However, effort was spent to fabricate the device prototype under thinking “the essence of the material could only be seen when it is made into a device”. Taking a long view, this was a good decision for the continuation of the R&D.

4.2 AIST period (2001~2007)

4.2.1 Establishment of the research center and proposal of the total solution

Before the waves of free economy changed the Japanese society, the R&D for social infrastructures such as power and communication was led by the electric power company and telephone company (current Nippon Telegraph and Telephone Corporation), and the private companies joined to participate in research under their abundant research fund. Under such privileged technological development, the obtained technological result may be rather over-spec but still could be used to satisfy the demands in Japan. However, as the management tightened up due to increased free competition, the development intent of the companies dropped due to the limited domestic demand projection and reduction in R&D funds. The contraction and corporate merging of the infrastructure R&D occurred, and the R&D environment deteriorated rapidly for power electronics as a whole as well as for infrastructure R&D. Around the world, global corporations such as Siemens, ABB, GE, and others were spending efforts assuming the developing countries as their clients. With such industrial background, we believed the public research institution must play a critical role.

Since AIST started from material research, the development of wafer and device process was conducted relatively smoothly. However, there were hardly any people who had experience developing the actual device that could be implemented to the converter, and this was only possible by inviting veteran researchers from industry. The presence of such invited researchers was extremely important in executing the total solution, along with the cooperation from the Energy Technology Research Institute, Nanoelectronics Research Institute, and Metrology Institute of Japan within AIST. The demonstration of the basic R&D as a whole in the "High-Tech Manufacturing" Research Program was a symbolic accomplishment of the total solution. The state-of-art joint research with the other research units of AIST through the AIST grant from the Ministry of Economy Trade and Industry (METI) played a major role in the construction of the facilities and the operation ("Development of Ultralow Loss Power Module Technology" (FY 2002~2006), "Development of On-CPU High-Speed High-Capacity Power Technology" (2004~2006), and "Development of Operation and Control Technology for Power Equalization System" (2003~2006)). The pioneering research that was conducted under the "IP Integration" research program, where the obtained patents were integrated, became a power in conducting further R&D for ultrahigh blocking voltage devices.

The prospect for a central research center for Japan for power electronics, a major basic technology for future energy saving centering on the SiC power device development, at AIST was not available until 2008. One of the greatest reasons was the R&D prototype manufacturing line for fabricating and providing the prototype devices to places where application could be expected was not up to a satisfactory level. To realize this, the construction of a device foundry, as well as the participation and collaboration of the researchers in system application who can present the required specification for device performance is mandatory. Since 2008, the potential for the former is beginning to take shape as the Industrial Transformation Research Initiative. We hope for the realization of the latter.

4.2.2 Improvement of device technology in the Open Proposal for Energy Saving

After the first five years of the fundamental development project, the section in charge of the project at METI demanded faster practical utilization, and did not approve the continuation of the basic research by the project. At that time, the SiC power device was taken up as future technology in the "Strategy for Energy Saving Technology"[Note 4]. We also held a symposium where the government discussed the expectation for energy saving by the SiC power device and the user companies discussed the applications, to raise the interest for the practical utilization of SiC[Note 5]. This effort led to five topics of the three-year NEDO open proposal for Energy Saving with the collaboration between the industry and the government. In these three years, the companies were able to demonstrate several ampere (A) class devices, and AIST was able to do a principle demonstration of MOSFET as ultralow loss device. Also, high-performance Schottky barrier diode that can directly lead to the performance demonstration for the converter and PIN diode was developed. These results continued on to the development of the NEDO "Inverter" project.

4.2.3 Establishment of ESICAT Japan, LLP

While it is essential to form the high-quality epitaxial film with controlled impurities concentration for device fabrication, the supply of epitaxial wafer was dominated by Cree, Inc. In FY 2005, with the agreement for joint research support, Showa Denko K.K., a company with experience in epitaxial growth, the Central Research Institute of Electric Power Industry, and AIST got together and a limited liability partnership ESICAT Japan was established. The technological topic was the practical utilization of carbon-face micro off-angle-face epitaxial wafer developed by AIST. The aforementioned "Inverter" project did not include the wafer development, and the development support was done through the information exchange on the correlation between the device performance and the wafer quality, as well as supply from the Japanese wafer manufacturers. Fulfilling the expectation, the supply of high-quality four-inch substrate was started in Japan. In the final stages of the project, by fabricating the four-inch prototype of the Schottky barrier diode, it was demonstrated that the quality of the epitaxial wafer was at a practical level. These activities contributed to creating the supply chain for the epitaxial wafers in Japan.

4.2.4 Coexistence with the GaN R&D

In the activities after 2001, we were occasionally forced to select between SiC and GaN. We stated that it was significant to visualize the innovations in power electronics while constantly comparing the advantages and disadvantages of the two. In the two NEDO projects for SiC, we included a GaN device topic as a side topic for the sake of comparison with SiC. As of now, it is determined that SiC is suitable for high-capacity devices of kV class, while GaN has great advantages in mobility and is promising as the high-speed switching device in the relatively low blocking voltage horizontal power device of less than kV. The GaN research at AIST supported the project in the form of material research in the concentrated research method, in the project for realizing the GaN high-frequency device for direct application of low-power consumption needed in cell phone stations (NEDO "Development of Nitride Semiconductor Low Power Consumption High-Frequency Device" (FY 2002~2006)). The GaN device went into the device phase slightly later at AIST, and its potential was shown in the development of the low-loss device for AC adapters in the NEDO Open Proposal for Energy Saving. For GaN, the key to its practical utilization is the increased quality of the GaN hetero-substrate on the Si wafer, which is hoped to be a low-cost wafer. After 2008, the research for the state-of-art application of GaN device will continue.

4.2.5 Construction of the device process line

Since the project started from material research and its scale was increased to device, converter, and system, we were always short of human resources, facilities, and equipment, and it was mandatory to obtain them. For the clean room facility (including the major equipment for lithography), we were initially totally dependent on the Nanoelectronics Research Institute, AIST. The procurement of R&D funds for the actual device, circuit, and module in the demonstration of the converter was approaching the limit as a single research unit at AIST. With the concentrated research in the two NEDO projects, active participation to the NEDO open proposals, a grant from METI to AIST to further promote the basic R&D, a grant to install large-scale facilities in the institute, and construction of the new building for nanotechnology research, we obtained the understanding and timely support, and finally were able to construct a manufacturing line for the two-inch prototype device. The two-inch line was improved as a place of R&D with industry, and collaboration with companies progressed through the sharing of the know-hows and transfer of intellectual property. In addition, the ultralow loss SIT and PIN diode mentioned earlier could now be fabricated at good yield. Through the joint research with companies, the developments are being conducted for the breaker for DC distribution system (NTT Facilities, Inc. etc.) and the high-capacity converter (Toshiba Mitsubishi-Electric Industrial Systems Corporation, etc.).

4.2.6 Training, international exchange, and collaboration of human resources

In human resource training, the researchers who were capable of thinking and projecting the downstream of their technology were nurtured through the seven-year experience at the research centers of AIST. We have dispatched people to industry. Contribution to the academia includes the activities in the SiC and Related Wide Bandgap Semiconductor Research Group of the Japan Society of Applied Physics and two active participations in the International Conference on Silicon Carbide and Related Materials (ICSCRM)[Note 6]. International collaborations included the activities at the Power Electronics New Wave (PENW) workshop[Note 7]. Through the exchanges at international conferences, we learned that people shared the common consciousness "while power electronics is important, it is an underlying support of society for which the social awareness is low". Information was exchanged among the people who shared the same thoughts at the Center for Power Electronics System (CPES) of the United States, European Center for Power Electronics (ECPE), and AIST. The PENW was held to create a common roadmap for power electronics. The footholds in international collaboration were created through these activities. When the Obama Administration started in 2009 in the United States, environment and energy were listed as important topics, and the R&D in this field is being strengthened. As the follower of CPES, a center for constructing a next-generation microgrid that incorporates renewable energy was established under the support of the National Science Foundation (NSF)[5]. The global competition and collaboration for grid standardization will become an important topic. We believe a quick action based on international perspective is necessary for Japan.

4.3 Industrial Transformation Research Initiative activities at AIST

The SiC Schottky barrier diode has become commercially available. Since it has the advantage of requiring small recovery current when switching, 30~40 % reduction of loss can be achieved by simply installing the SiC Schottky barrier diode as the free wheeling diode in combination with the Si-IGBT device. Therefore, it is almost certain it will be used in diodes. As the market scale of the SiC device is becoming visible, we are now out of the three-party deadlock and are receiving positive feedbacks from various fields. The topic of the Industrial Transformation Research Initiative at AIST is a timely decision to acquire the related intellectual property for the converter application which was lagging behind because we had no supply of the device chip. The main required specifications for the device are different according to the application (Fig. 14).

It is important to consider the changes in the system and the new systems, and not just the advantages of the system from the advantages of the new converter. To do so, it is necessary for the company people to experience using the actual SiC device, as well as the exchange of opinions with various application development fields, in an actual place of joint work where the inadequacies can be pointed out. It is necessary to conduct a LINUX-style development where the source code of the basic software is disclosed and further developments are solicited from the users. This is a giant step in the *Full Research* for the practical utilization of the new semiconductor device. It can be positioned as the work of constructing the infrastructure in developing the future energy saving system. In quickly executing such large-scale R&D topics, the role of the Industrial Technology Architect (an AIST terminology) who conducts the integration of the funds, facilities, and joint research contracts is crucial. The device evolves as it accepts the required specifications from the system. We are at a phase where the people who bridge the device and system application play extremely important roles. AIST is expected to play the role as an integrator.

5 Future issues

The new government of Japan that came to power in September 2009 is calling to the world for “25 % reduction of greenhouse gases by 2020 compared to 1990”. In the Tsukuba region, there is a plan for the formation of the nanotechno innovation center, in the style of the Interuniversity Microelectronics Centre (IMEC) of Europe and the industry-academia collaborative research in Albany, USA. Power electronics is one of the topics. The clarification of the potential and promotion of further SiC basic research was selected as one of the 30 topics of the “Funding Program for World-Leading Innovative R&D on Science and Technology” of Japan. The R&D for the practical utilization of new semiconductors does not develop sequentially like “wafer → device → system application”. The individual R&Ds progress in a spiral form, for example, in response to “a larger wafer diameter is required” or “higher quality is demanded” with the advancement of device development. We expect that the industry-academia-government will join together to engage in the pioneering basic R&D to ensure practical utilization. We need an integrated R&D that looks at the future of power electronics as the key technology that supports the transformation of the energy infrastructure.

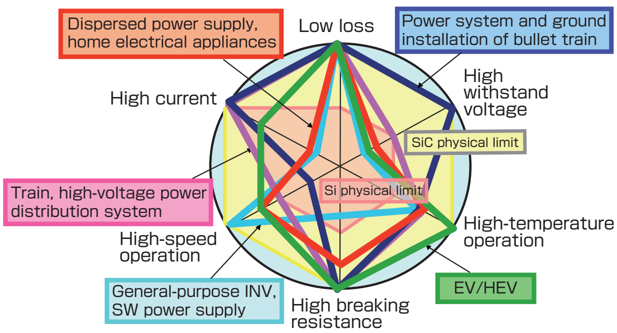


Fig. 14 Conceptual diagram of the application and required device performance

Some of the device performances are in trade-off relationships (for example, low loss – high breaking resistance – high-speed operation). The optimization (tuning) of the device performance according to application is important.

Acknowledgements

I thank Professor Sadafumi Yoshida, Saitama University (currently visiting researcher at AIST) for his judicious advice on this paper. He is the pioneer of the R&D for SiC material and device and has supported our efforts from the beginning.

Notes

Note 1) The structure of the paper was arranged according to the instructions provided by the reviewers, considering the objective of this journal. Therefore, the periods during which certain organizations were active and the periods of the projects do not necessarily match.

Note 2) 1st International Workshop on Ultra-Low-Loss Power Device Technology (UPD2000), May31~June 2, 2000, Nara, Japan (organized by the Research and Development Association for Future Electronic Device).

Note 3) The group led by Professor Madar of the Centre National de la Recherche Scientifique (CNRS), Grenoble, France cooperated in this simulation.

Note 4) The importance of energy saving in the power electronics application was indicated in the “Strategy for Energy Saving Technology” (Energy Technology Policy Division, Agency for Natural Resources and Energy, June 12, 2002). In the revised edition, SiC is acknowledged as the energy-saving device technology for power electronics.

Note 5) Special Symposium “New Start of Energy Saving Technology Development ~ New Developments in Power Electronics”, held on November 25, 2002, at the Zenkyoren Building, Tokyo. Organized by the Information Technology Research Institute, AIST.

Note 6) “Research Session on SiC and Related Wide-Gap Semiconductor”, Japan Society of Applied Physics; International Conference for Silicon Carbide and Related Materials (ICSCRM01, Tsukuba); ICSCRM07 (Ohtsu).

Note 7) 1st Power Electronic New Wave (PENW) International Workshop, held at Hatsumei Kaikan, Tokyo, on April 11, 2005, organized by AIST, supported by FED. 2nd PENW, on June 15, 2006, organized by PERC, supported by FED. 3rd PENW, on January 2008, AIST.
European Center for Power Electronics (ECPE), Germany: an industry-academia-government collaborative effort led by Siemens AG. Established in 2003.
Center for Power Electronics System (CPES), USA: one of the NSF-supported engineering centers composed of five universities and over 80 companies, led by the Virginia Polytechnic Institute and State University. Established in 1998.

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Discussions with Reviewers

1 Overall structure

Comment (Yoshiro Owadano, Environment and Energy, AIST)

The first draft is written chronologically, and the social situations, ways of thinking, events leading up to the research, and the results are presented as a mix. Therefore, it is interesting as an article, but it is difficult to follow the logical development as a paper. To contribute to the future discussion with some generalization as “synthesiology”, why don’t you rearrange the structure as follows: 1) research objective, 2) setting of the individual issues, 3) strategy for solving the issues, 4) execution and results, 5) evaluation of the strategy, and 6) future issues and strategy?

Comment (Hiroshi Tateishi, New Energy and Industrial Technology Development Organization)

The first draft is a chronology and commentary of the SiC device development of the past 20 years. Please revise the structure and reconsider the logical development so it will be more suitable as a research paper of synthesiology.

Answer (Kazuo Arai)

I revised the draft as instructed, although there may be some overlaps.

2 Clarification of the research strategy

Comment (Yoshiro Owadano)

The “Innovation of power electronics” in the first draft contains important points, and I think it should be discussed in the beginning. In that case, please organize and discuss whether you intended to replace the silicon with SiC, or whether you intended to replace the mechanical breaker and relay that are fairly functional as they are at the moment, and what would be the advantages of such replacements.

Answer (Kazuo Arai)

I may be unable to discuss too deeply, but I indicated the possibilities and the points of the development. If the cost approaches silicon and the reliability is established, I am certain that the kV or over power devices will become SiC.

3 Reasons for selecting power electronics and SiC

Comment (Yoshiro Owadano)

While it may be true that increasing the percentage (electrification ratio) of using energy as electric power is important, I think you should be aware that is not directly linked to the diffusion of power electronics. Please indicate the uses in which the device must be a power electronics device, specifically a SiC device, and how it is expected to become diffused.

Answer (Kazuo Arai)

The fact that it is not directly linked is the problem, and I think that’s because there are problems and concerns about the cost and reliability of power electronics. Innovations must be done to remove such concerns, and while the SiC device has the potential, there are still many issues that must be solved. I think the strategy for practical utilization is how to overcome the issues considering the external conditions.

4 Reasons for selecting SiC

Comment (Hiroshi Tateishi)

I think you should provide a simple explanation on why you selected SiC as your starting point or the central target among wide-gap semiconductors. It may be obvious to the researcher in charge, but it is the first question for a non-expert.

Answer (Kazuo Arai)

I added the explanation at the beginning of section 3.1.1. The selection of SiC was the starting point.

5 Changes in research strategy

Comment (Hiroshi Tateishi)

I suppose you did not necessarily have a clear long-term strategy from the beginning, but the specs and the strategy evolved as you looked at the relationships between material, practical material, device and system as the research progressed.

Answer (Kazuo Arai)

This was an important point in 2001. I added the explanation in the beginning of subchapter 3.2.

6 Content of “total solution” and “power electronics innovation”

Comment (Yoshiro Owadano)

The original meaning of the phrase “total solution” is to take measures by integrating various methods to solve a major issue. I don’t think its meaning is the same as “integrated research”. Please state the issues that must be solved and clarify the meaning of the term “power electronics innovation”.

Answer (Kazuo Arai)

1) “Total solution” is used in the sense that various methods are integrated to solve a certain major issue. The major issue that must be solved for the practical use of the new semiconductor was the “solution of the three-party deadlock”. To do so, the linear R&D model of “wafer → device → application development” was insufficient, and it was necessary to deal with the issue from three directions (methods).

2) The “power electronics innovation” is a development of “[low loss + high frequency] → low cost converter → ubiquitous power electronics device”.

7 Content of “integrated research”

Comment (Yoshiro Owadano)

In “integrated research”, I’m sure there were shift of emphasis as time went by, allotment of limited resources, and walls between different topics. It will be very useful if you describe how you dealt with those issues.

Answer (Kazuo Arai)

Since this study started from almost zero, we recklessly engaged in whatever we thought was necessary, and were always hungry. If we could not fabricate the device on our own, we could not see any prospect. Therefore, funds were invested in the expensive equipment and facilities for the device process. I added the description of this situation.

Development of single-crystalline diamond wafers

— Enlargement of crystal size by microwave plasma CVD and wafer fabrication technology —

Akiyoshi Chayahara ＊, Yoshiaki Mokuno, Nobuteru Tsubouchi and Hideaki Yamada

[Translation from *Synthesiology*, Vol.3, No.4, p.272-280 (2010)]

Industrial application of diamond has been limited to the use of its hardness, e.g., in machining tools, because large size crystals of diamond are difficult to synthesize and very expensive. If these problems are solved, it can be used for various purposes. Diamond is called ‘an ultimate semiconductor’ and is located after SiC or GaN in the semiconductor roadmap. If power electronic devices with diamond are realized which utilize its operability under high temperature and the highest thermal conductivity among all materials, the inverters for automobiles can be operated without cooling devices, which lead to energy saving through the reduction of power loss as well as the reduction of weight of the cooling system. The purpose of this paper is to report the process of enlarging the size of single-crystalline diamond using vapor phase epitaxy and the fabrication of diamond wafers.

Keywords **:** Single-crystalline diamond, microwave plasma CVD, crystal growth

1 Introduction

Until recently, the single-crystal diamonds were industrially manufactured using the high-temperature high-pressure method. The Ib type or the yellow crystals containing nitrogen are mass-produced for use in machine tools. Single crystals with high purity and low defect can be synthesized, and it is also possible to manufacture near-perfect single crystals to be used as dispersive crystals for radiated light[1]. However, the size limit of the single crystal using the high-temperature high-pressure method is about 1 cm, and further increase in size is difficult because that will require large-scale pressure equipment. In contrast, the chemical vapor deposition (CVD) method used for the synthesis of polycrystalline diamond and homoepitaxial film has less size limit compared to the high-temperature high-pressure method. Therefore, there are several R&Ds for the single crystal synthesis using the CVD method to increase the size and to reduce the cost. Our R&D objective is to use the substrate in the next-generation power devices, and we aim to fabricate a 2-inch wafer needed for the manufacture line of the current prototype device. The single-crystal substrate with maximum 1 cm size that can be fabricated by ultrahigh-pressure synthesis is Ib type, and it is very expensive at 1 to 2 million yen. Cost reduction by one digit or more is expected by using the CVD method.

The reason that the CVD method has been used only for the synthesis of diamond film but not for the synthesis of bulk crystal until recently was because the growth speed was slow and the single-crystal growth could not be maintained over a long time due to the occurrence of abnormal grains. The solutions to these issues are the main topics in the research for the single-crystal CVD diamond synthesis.

In this paper, we shall explain the vapor deposition growth of diamonds, and then describe the increased high plasma density and nitrogen addition to solve the aforementioned issues in the single-crystal CVD diamond synthesis, particularly for the homoepitaxial growth. Then we shall address the development of the methods for shaping the diamond, an ultra-hard material, into the form of a wafer.

2 Development of the diamond synthesis by vapor deposition

The chemical vapor deposition (CVD) is a method where raw material gas (in the case of diamond, hydrocarbon gas such as methane and hydrogen) is broken down by heat or plasma under subatmospheric pressure, and the growth seeds produced undergo a chemical reaction on the substrate surface to grow into a diamond film[2]-[13].

The CVD synthesis of diamond based on thermal decomposition published in the 1950s had extremely slow growth rate, and was an unrealistic method due to the graphite inclusions. By the end of the 1960s, it was known that the graphite components could be selectively etched due to the presence of atomic hydrogen. However, the CVD diamond research rapidly lifted off in 1982~1983, after the National Institute for Research in Inorganic Materials (currently National Institute for Materials Science (NIMS)) published the production method of atomic hydrogen, and reported that it was possible to synthesize diamond at the growth rate of μm/h level[14][15]. These methods were called the hot filament CVD and microwave plasma CVD methods. In these methods, the methane gas diluted by hydrogen was decomposed by tungsten filament or microwave plasma heated to about 2200 ºC, and the diamond grains were grown

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on the substrate of about 800 ºC under decompression. Several CVD methods were developed since then, but these two methods were innovative, as they are still widely used in the CVD diamond manufacturing and R&Ds.

In the general CVD method, the raw material gas such as the hydrocarbon gases are decomposed under decompression, the non-diamond substrate is nucleated, and the polycrystalline diamond film is deposited. Such polycrystalline film has excellent properties for various uses such as coating tools. The production of atomic hydrogen and the decomposition of raw material gas can be accomplished by various methods. Depending on the method of the decomposition (activation), the methods can be roughly divided into thermal CVD and plasma CVD. While the decomposition of the raw material gas in the thermal CVD process is achieved by thermal activation, it occurs by electron-molecule reaction in the plasma CVD. Thermal CVD process includes the hot filament method and the combustion flame method such as the oxygen-acetylene torch. Plasma CVD method includes the microwave plasma, DC plasma, DC plasma jet, and RF plasma methods.

In the hot filament CVD method, the film can be formed on a large surface area, since large equipment can be manufactured at relatively low cost. It has already been realized as the polycrystalline diamond coating method for machine tools. However, the filament material (tungsten, tantalum, rhenium, etc.) heated to high temperature may become included in the film as impurities, and the growth rate is slow.

The microwave plasma CVD has few inclusions of impurities since the electrodeless discharge is used, and it is possible to form semiconductor-quality film. Although the growth rate was slow, the speed has been increased as explained later[16], and the microwave plasma CVD is used in almost all cases of bulk single-crystal synthesis by CVD.

The characteristic common in the CVD diamond synthesis methods is the high-concentration hydrogen gas. Until recently, hydrogen concentration of 99 % or higher was necessary to obtain the diamond with small graphite component. In general, it is believed that the high-concentration hydrogen produces large amount of atomic hydrogen that plays an important role in the diamond CVD process. The diamond synthesis occurs as the radicals from the gas attach to the growth surface and then detach, that is, a surface reaction process takes place. When the diamond crystal grows, the nucleation of the diamond occurs first, and it is necessary to prevent the diamond growth surface to transform into a graphite phase. To do so, it is necessary for the high-concentration hydrogen atoms to bond with all the dangling bonds present on the diamond growth surface. It has been confirmed in the heating experiment that the diamond structure is relatively stable in hydrogen. In ultrahigh vacuum, the diamond surface graphitizes at about 900 ºC, but the diamond structure is maintained up to 2200 ºC when heated in hydrogen[17]. In oxygen, the mass decrease due to oxidation starts at about 585 ºC[18], and the diamond oxidation progresses along with the graphitization of the surface. The diamond growth is explained as follows. In the process of the formation of hydrogen molecules resulting from the reaction of bonding hydrogen that covers the growth surface with hydrogen atoms in the gas, holes (dangling bonds) are formed after the hydrogen is pulled from the growth surface. Next, methyl radical CH_3 produced by the decomposition of the raw material gas (the hydrogen atoms play a part in this reaction) bonds with the holes and growth occurs. Moreover, the atomic hydrogen selectively etches the graphite layer that deposits simultaneously with the diamond. This is useful in reducing the graphite component within the crystal grain boundary in the CVD polycrystalline diamond synthesis. The general procedure is to add oxygen to the raw material gas. In etching with oxygen, the selected ratio of graphite and diamond is not as high as with hydrogen, but since etching can be conducted effectively at low temperature, oxygen addition is useful in reducing the temperature of the diamond growth condition. Also, for the composition ratio of the carbon-hydrogen-oxygen in the raw material gas, the Bachman diagram[19] that shows the range of composition ratio in which the diamond growth is possible is widely known.

In the diamond crystal growth technology, the formation of the diamond nucleus called the bias enhanced nucleation (BEN)[20] is important. BEN is used as a nucleation technology for the heteroepitaxial growth on different substrates and for the growth of polycrystalline diamond and nano-diamond film. In the case where the polycrystalline diamond is grown without using the nucleation by BEN, the substrate must be pretreated by mechanical or ultrasound polishing in organic solvent using diamond abrasives before the growth process. This is called the “seeding” process where fine diamond grains are embedded into the substrate, and these become the seed crystals from which growth begins. BEN is a method to replace this. The substrate is charged with negative bias in the plasma with relatively high hydrocarbon concentration. Highly dense diamond nuclei are formed. To grow diamond on these nuclei, the normal growth without bias charge is conducted following the BEN process. Only the stable area formed during the BEN process survives to continue growth.

The film grown after the seeding process becomes polycrystalline where the crystal orientation is random in the growth face, while in BEN, the orientation of the seed crystals may align with the substrate, and the diamond film that grows upon this substrate will be oriented accordingly. This allows heteroepitaxial growth on single-crystal iridium

Ir, platinum Pt, and SiC. Since large diameter substrates such as the Si or SiC wafers have become available, the product realization of large single-crystal substrate using heteroepitaxial growth is being attempted, yet the improvement of crystal formation is an issue.

We aimed to fabricate a large diamond crystal using the homoepitaxial growth with excellent crystallization, by using the microwave plasma CVD method that has smaller surface area than the hot filament method but has relatively faster growth time that allows prolonged synthesis.

3 Diamond single-crystal synthesis by microwave plasma CVD method

The high-speed synthesis of diamond single crystal was conducted using the general-use ASTeX microwave plasma CVD device (2.45 GHz, 5 kW; Seki Technotron Corporation) shown in Fig. 1. Refer to Reference[21] for the microwave plasma CVD device. Thinking that a high-density plasma production was needed for high-speed growth, the form of the Mo substrate holder to concentrate the plasma onto the substrate was modified[22]-[25].

The {100} face of the Ib type diamond synthesized by high-temperature high-pressure method was used as the seed crystal substrate. Methane and hydrogen were used as raw material gases, with flow rate of 60 and 500 sccm respectively, pressure of 21 kPa, and substrate temperature of about 1100~1200 ºC. The substrate was heated by plasma. The luminescence from the plasma was collected by optical fibers and monitored by a spectroscope.

The synthesized growth layer was evaluated by the locking curve method using precise x-ray diffraction and Raman scattering spectroscopy. The half-value width of the (400) face locking curve that clearly showed the crystal quality of the synthesized single-crystal diamond was minimum 7.6 sec so far, and this was equivalent to the high quality Ib synthesized by the high-temperature high-pressure method.

3.1 Growth rate

As mentioned earlier, one of the reasons the CVD method was used to synthesize the polycrystalline diamond film but not to synthesize the bulk crystal until recently, was because of the slow growth rate. For example, compared to the liquid phase growth of 1~2 mm/min in the Si ingot pull-up method and 0.2~1 mm/h of SiC by the sublimation method, diamond growth rate of a few μm/h is too slow for the bulk crystal method. To increase the growth rate of diamond in the plasma CVD method, it was necessary to raise the raw material gas pressure and to increase the amount of activated seed supplied to the growth surface by increasing the density of the plasma by applying high power.

There are several reports of the increased growth rate by addition of nitrogen[22][26]. Figure 2 shows the dependency of growth rate on nitrogen flow rate. The figure shows the two types of substrate holder used for the growth. The growth rate increased in both substrate holders as the nitrogen flow rate increased. While the growth rate in conventional microwave CVD was 10 μm/h or less, it reached 50~100 μm/h by the combined effect of increased plasma density and nitrogen addition. Although the growth temperature differed in the two substrate holders, it was known from experiments that the change in growth rate within this range of temperature difference was small. Therefore, Fig. 2 shows the effect of nitrogen addition as well as the large change in growth rate depending on the form of the substrate holders. The degree of concentration of the microwave field changes according to the form of the substrate holder, and more the concentration the faster it is due to the increased plasma density around the substrate.

3.2 Control of abnormal grain growth

The {100} face is often used as the crystal face orientation of the epitaxial growth substrate. The reasons are because the bicrystal is less likely to occur compared to other facial orientations, and because polishing of the {111} face is difficult for structural reasons. When the epitaxial growth is done on the {100} face, the abnormal growth of the abnormal

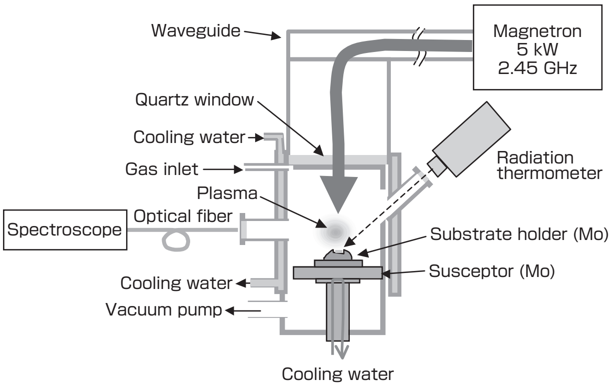

Fig. 1 ASTeX type microwave plasma CVD device

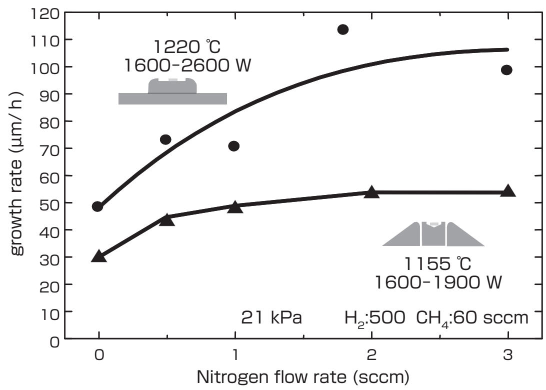

Fig. 2 Dependency of the growth rate on nitrogen flow rate

nucleus occurs in insufficient growth conditions. In many cases, this abnormal nucleus forms a pyramidal structure with grain of {111} orientation growing on top of the {100} face. This is thought to originate from the dislocation within the seed crystal, polishing flaw, etch pit, or fluctuation during growth. The methods to effectively control the occurrence and spread of such abnormal nuclei include the α parameter control, step flow growth using an off-substrate, and nitrogen addition. These are explained below.

1) α parameter control

In diamond crystal growth, the facets (automorphic face of crystal) that manifest are mostly {111} and {100} faces. Setting the growth rate perpendicular to those faces as V_{100} and V_{111}, the α parameter can be defined as follows[27][28]:

$$\alpha = \sqrt{3}\, V_{100}/V_{111}$$

Since V_{100} and V_{111} have different dependencies for the growth conditions such as pressure, methane concentration, and temperature, α changes according to the growth conditions. In the case of polycrystal synthesis, the change of α is used for controlling the orientation. That is, the growth continues even if the growth is started from a nucleus with specific orientation, and as the film grows, the crystal orientation near the growth surface becomes oriented in the direction determined by α. Also, the form of the crystal grain is determined by α. At about α=3, the polycrystal growth assumes the <100> orientation, and is effective in controlling the occurrence of abnormal nuclei in the growth on the {100} face used often as single-crystal growth surface. In this case, if the origins of the abnormal nuclei are present and the {111} oriented grains grow on top, the growth of {100} around it is fast, the abnormalities become buried, and they will not be able to grow into large abnormal grains. However, in this condition, the defects that occur during the dislocation and growth on the substrate are carried over to the growth direction, and may remain as perforating dislocations. Also, since the α differs by devices, the condition that yields a certain α is explored by mapping the α by changing the growth conditions.

2) Step flow on the off-substrate

It is known that the step flow growth occurs when the growth is done on a polished off-substrate that is inclined within a few degrees from the {100} face. When the step passes this part faster than the growth of the abnormal nucleus on the terrace, the abnormal nucleus cannot grow and flat growth can be expected. It is an effective method for forming a semiconductor grade film[29].

In the case of the growth of a large crystal, even if the growth is started using the off-substrate as the seed crystal, the step growth occurs initially over the whole surface of the substrate as in the film growth, but the off is disengaged at the edge of the substrate, and finally the entire growth surface becomes the {100} face[30]. Of course, the effect of controlling the abnormal nuclei cannot be expected after that.

3) Nitrogen addition

During the epitaxial growth on the {100} face, the occurrence of the abnormal nucleus can be controlled by adding a small amount of nitrogen to the raw material gas. The α increases with ultralow volume addition of nitrogen. When the amount is increased, the {111} face can no longer grow normally and becomes polycrystalline. Either way, the growth of the {111} face is inhibited, and as a result, the abnormal nuclei are controlled. This method is used when synthesizing large single crystals by maintaining high-speed prolonged growth. However, when nitrogen is added, deep donor level and carrier trap are introduced and an insulating body is formed. Also, due to the defects accompanying nitrogen, absorption occurs in the visible light range. The control of the {111} face growth by nitrogen addition is thought to occur as the nitrogen atoms bond strongly to the {111} face at three coordinates, and the carbon atoms cannot bond to the {111} face covered with nitrogen[22][26].

Figure 3 shows the differential interference microscope image of the growth surface at various nitrogen flow rate. When nitrogen is not added, a pyramidal projection (growth hill) can be observed, and there is a typical surface form of the diamond synthesized by the CVD method on the {100} surface. This growth hill remains in the crystal as a large structural defect, and is a factor that inhibits the formation of a thick film by prolonged epitaxial growth. The growth hill is not seen at all when nitrogen is added, but rough surface caused by macro step bunching is observed. When more nitrogen is added, the steps become nonlinear and disturbed. When nitrogen is added, the surface roughens, but since there will be no growth hills, thick film and bulk formation by prolonged growth becomes possible. Conventionally, the single-crystal growth by CVD method was difficult due to the occurrence of abnormal nuclei, but as the result of control of abnormal grain growth by the addition of ultralow volume of nitrogen, the bulk single-crystal growth by CVD method became possible.

3.3 Size increase

The photograph of the sample synthesized over a long time on a 1 cm square substrate is shown in Fig. 4. In the {100} growth by nitrogen addition, the crystal diameter does not expand as shown in the photograph. To obtain the large diameter, the lateral face ({100} face) of the grown crystal is polished, and the growth is repeated on top of that face as shown in Fig. 5. Figure 6 shows an example of the crystals obtained by this method.

The similar lateral growth is seen in the method for reducing defects for the SiC single-crystal growth called the RAF method[31]. The sublimation method is used for the single-crystal growth of silicon carbide SiC, which is expected to be in practical use as power semiconductor in the near future. In conventional SiC sublimation method, the growth takes place along the c axis <0001>, whereas in the RAF method, the dislocation structure change by the {1120} and {1100} faces called the a-face are used to reduce the dislocational defects. Since the growth is repeated toward the a-face direction, it is called the repeated a-face (RAF) growth method. From the ingot grown in the c-face direction, (1) the {1100} face crystal is cut out and the growth is done on that face. Next, (2) {1120} face crystal is cut out, and growth is done on that face. After repeating (1) and (2) several times, the seed crystal of the c-face is cut out from the ingot, and this is used for the c-face growth. The conventional c-face grown ingot has several dislocations, but the dislocation of the seed crystals is reduced by the a-face growth. Majority of the dislocations are present parallel to the seed crystal face, and it is thought that the defects parallel to the crystal face are not carried over during the a-face growth.

The motivation for developing the RAF growth method for the SiC single crystal was the reduction of crystal defects such as micropipes. In contrast, the {100} face repeated growth method in the CVD diamond was primarily done to obtain a larger diameter. In the growth condition of ultralow volume nitrogen addition, the growth was only in the <100> direction, and an increase of the crystal diameter by growth could not be expected. There are dramatic differences in the diameter and quality of the SiC and diamond wafers. Although SiC is more than 20 years ahead, it is interesting that the lateral repeated growth was proposed at almost the same time.

3.4 Wafer fabrication

Since diamond is the hardest material, it is not easy to process. Therefore, its formation into a wafer form necessary for the manufacture of semiconductor devices is very difficult. Laser cutting is used to process industrial diamonds, but the losses due to cutting reserve and processing time are issues. Also, flatness and low defects are required in the precision polishing technology. “Direct wafer technology” and mosaic method have been developed as methods for wafer fabrication.

In the direct wafer technology[32], ion is implanted to the single-crystal diamond that will be used as a seed prior to the growth, and a defect layer is introduced immediately beneath the surface. After vapor deposition, the defect layer assumes a graphite structure, and can be removed by electrochemical etching. The seed crystal and the growth layer have diamond structures and are very stable chemically, and are not etched chemically. The seed crystal and the growth layer are separated to form a plate diamond (Figs. 7, 8). Some small parts of the seed crystal will be lost during the separation, but this thickness is only about 1 μm or the depth of the ion implantation. Therefore, the ordinary seed crystal can be used repeatedly, and the separated crystals can also be used as seed crystals.

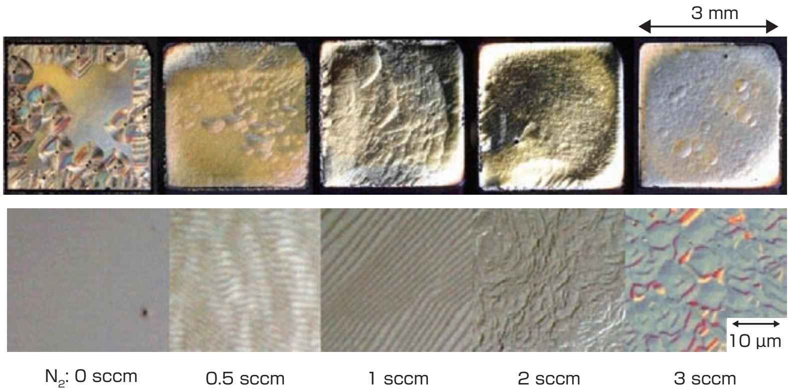

Fig. 3 Dependency of the surface form on nitrogen flow rate observed by a differential interference microscope
Top: Macro image (low magnification). Bottom: micro image (high magnification).

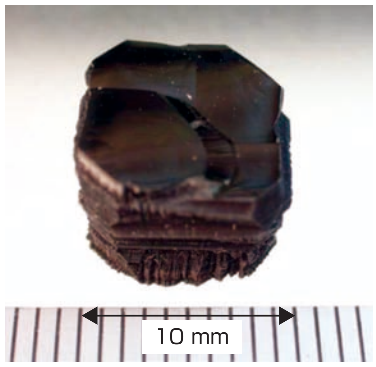

Fig. 4 CVD single-crystal diamond
Weight: 2 g (10 carat)

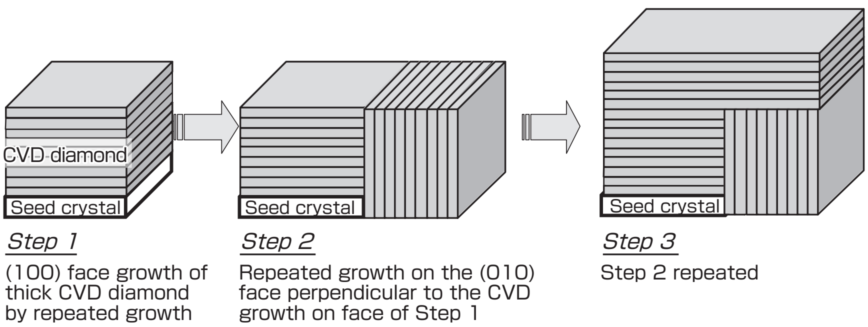

Fig. 5 Size increase of crystal by repeated lateral growth

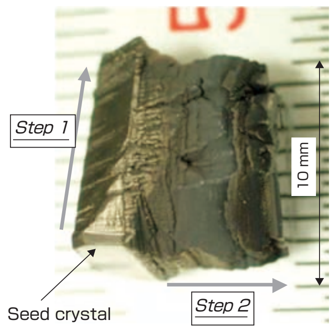

Fig. 6 Example of lateral growth

Although such separation method has been studied at several research institutes[33]-[46], they were limited to small size and the etching took a long time. The maximum size reported in the literature was about 3~4 mm square, and there was a barrier of conventional technology. The authors started to consider the etching method, and as a result, found a method to form dramatically large surface areas and at higher speed. Since, in principle, there are no problems in scaling up or mass processing, it is considered to have excellent prospects in the future diamond wafer manufacturing technology.

The mosaic method[47]-[54] is a method where the small single-crystal diamond plates of a few millimeter square are closely packed, and the CVD growth is formed and bonded on top. Although the junctions cannot be used as a device, this method was developed to use the entire structure as a wafer and to apply it in the semiconductor process. The junctions produced abnormal grains, but it was found that the abnormal grains at the junction could be reduced dramatically when several crystal fragments fabricated from the same seed crystals using the direct wafer technique were bonded[55]. It is thought to occur since the face orientation of the crystal fragments align automatically. We used this method to fabricate a mosaic wafer of about 1 inch, and we now have ideas for a mass production method by applying the direct wafer technology using the mosaic wafer as the seed crystal. The mosaic method can be used for size increase easily, and is a method that can fulfill the immediate demand for size increase.

3.5 Smart cut and direct wafer technique

As one of the manufacturing method for the silicon-on-insulator (SOI) wafer that can operate the device at high speed and at low power consumption, a cutting method using the hydrogen ion implantation is used[56]. This cutting method that uses hydrogen embrittlement is called “smart cut” or “ion cut”, and is a process where the surface of the single-crystal wafer of the semiconductor such as that of silicon is peeled off at thickness of submicron to micron level (corresponding to the depth of ion implantation). The basic process for SOI wafer fabrication by the smart cut method is as follows. (1) SiO_2 insulating layer is formed on the silicon wafer surface by thermal oxidation. (2) Hydrogen ion is implanted. (3) Hydrophilic treatment is done, layered with other silicon wafers, and bonded at room temperature. (4) Heat treatment is done at 400~600 ºC, and the layers are separated at several micron thickness from the wafer surface that was implanted with hydrogen ion. This is possible due to the gaps formed by aggregated hydrogen. (5) Junction boundary is treated at 1000 ºC or more. (6) Separated wafer surface is polished. The above process is called the direct bonding method. Other SOI wafer that uses ion implantation includes the “separation by implanted oxygen (SIMOX)” wafer. This is a method where an embedded oxidation film is formed from the silicon of the wafer and the implanted oxygen by high-temperature treatment after the implantation of oxygen ion to the silicon wafer, but no separation is done.

From the experience of the embedded SiC layer formation using the high-temperature carbon ion implantation to the silicon wafer[57][58], we obtained the knowledge to apply the aforementioned ion implantation technique, and we considered the use of ion implantation as the method for creating the wafer from diamond, a material difficult to process. A thin film such as SOI is not necessarily needed, but to manufacture a wafer with thickness of 0.3 mm or more, epitaxial growth is necessary after ion implantation. In the smart cut, the separation may occur during the growth by heat treatment at around growth temperature of 1150 ºC. To prevent this, in the direct wafer method, the amount implanted is the amount where the implanted layer transforms into graphite, and the growth layer is separated by removing the graphite layer by etching after growth. There is a pioneering study by Marchywka *et al.* for the etching of the graphite layer[59].

4 Conclusion

We demonstrated that it was possible to synthesize a 12 mm single-crystal and 25 mm mosaic crystal using the plasma CVD method, surpassing the maximum size of 1 cm square using the high-temperature high-pressure method. Also, it was shown that a 2-inch size was possible using polycrystals in the direct wafer technology. In the next 1~2 years we plan to fabricate a 2-inch mosaic crystal. The verification for the usability as a wafer is in progress right now, but at

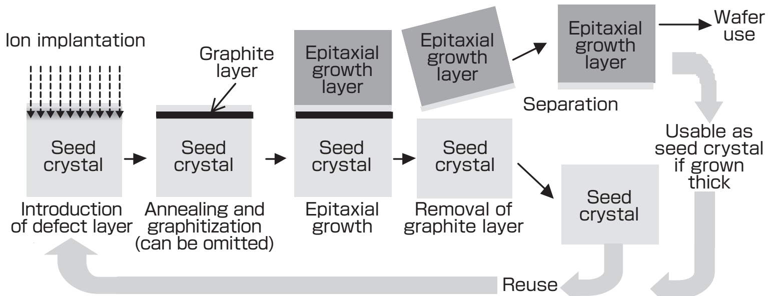

Fig. 7 Direct wafer technology

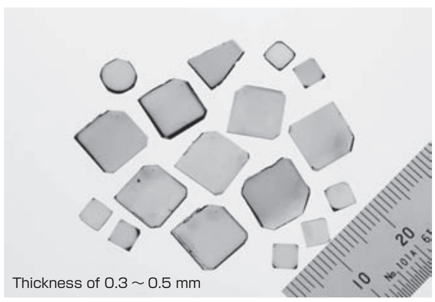

Fig. 8 Single-crystal diamond plate fabricated using the direct wafer technology

the least, it has been shown that it can be used in place of the ultrahigh-pressure substrate[60]. To obtain higher quality, the reduction of dislocation density is necessary, and we are aware that the pretreatment of the epitaxial growth is important. In the case where there is nitrogen related absorption in the visible range and this is a problem for optical use, it is possible to create a transparent product if it is grown without nitrogen addition. However, at this state, the growth rate will be 10 μm/h or less. As it can be seen from the fact the CVD polycrystalline diamond coating is widely used for machine tools, the cost of the CVD process itself is not particularly expensive. If the mass production of CVD diamond is realized in the future, the several millimeter single crystals will become readily available, and 1 cm or over will be possible. As a rough estimate, for high-temperature high-pressure synthesis, when the price of a Ib type 1 cm square single-crystal diamond plate is about 1~2 million yen, it will be a digit lower with CVD. This is dependent on the scale of mass production and the corporate strategy, and it is also necessary to consider costs other than synthesis such as shaping. In the case of diamond, since there are demands besides the semiconductor, we can expect the shift to the CVD synthesized product with excellent cost efficiency even with current manufacturing technology. An AIST venture[61] based on the single-crystal diamond manufacturing technology described in this paper was established, and is supplying samples. If the diamond semiconductor manufacturing is realized, there will be great demands, and as a result, we may see new uses for the single-crystal diamond that will become more readily available.

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Discussions with Reviewers

1 Clarification of the development goal and comparison of the existing technologies

Comment (Kazuo Igarashi, Institute of National Colleges of Technology, Japan and Hisao Ichijo, Tsukuba Center, Inc.)

In this paper, the ways of using the single-crystal diamond wafer is not stated clearly. For example, if the target is for use in the power device substrates, I think you will have a paper with better scenario scheme by stating the size you set as the target for size increase as indicated in the subtitle, where you stand now in achieving the target, and the superiority of the direct wafer fabrication technology and its applicability to size increase.

Also, there are technological developments to address the topics of high-speed growth, low defect crystal, and size increase. I think people can better understand the result of this research if you provide numerical comparison (such as how much faster it is) with the existing or other technologies.

Answer (Akiyoshi Chayahara)

The objective of this development is the utilization in the substrate of next-generation power devices. We aim to create the 2-inch wafer needed for the manufacturing line of the prototype device. Currently, we can fabricate a maximum 1 cm single-crystal substrate by ultrahigh-pressure synthesis, and this is called the Ib type that costs 1 to 2 million yen. The size and cost make its use difficult. The direct wafer technology can be applied to a substrate with 2-inch diameter for polycrystal. We believe it is possible to attain the target size, and a one-digit decrease in price can be expected.

For the numerical comparisons with existing or current technologies, other than the crystallization property, I added sentences that contain the numerical values in the appropriate places in the text to make the comparisons easier.

2 Quality of the wafer

Question (Kazuo Igarashi)

While it depends for what the single-crystal diamond wafer is used, I think the quality (transparency, impurity concentration, concentration of crystallizations/defects, etc.) must be guaranteed. What is the level of the current wafer fabricated by the microwave plasma CVD method in terms of quality? If further improvement of the quality is needed, what key technologies are required?

Answer (Akiyoshi Chayahara)

When synthesizing the single-crystal using the microwave plasma CVD method, we add ultralow volume of nitrogen to control the macro defect called the abnormal nucleus. The crystallization to the same degree as in the ultrahigh-pressure synthesis Ib type has been obtained from the half-value width of the x-ray locking curve. For semiconductor use, this level is sufficient as the replacement for use in the R&D of the devices that conventionally used the Ib type substrate. To further develop the research, the reduction of the dislocation density is necessary, and we are aware that the pretreatment of the epitaxial growth is important. Currently, the disadvantage of the direct wafer technology using the electrolysis etching is that the conductive substrate cannot be separated. Therefore, a technology that enables this is awaited. For optical use, there is a problem since nitrogen-related absorption occurs in the visible range. When growth is done without nitrogen addition, transparency can be obtained, but currently the growth rate is 10 μm/h or less. Or, the transparency can be obtained by treating the nitrogen added diamond with ultrahigh-pressure. In either case, cost will be an issue.

3 Selection and integration in the wafer technology

Comment (Hisao Ichijo)

Since you explain the reasons for employing the microwave plasma CVD, if you briefly explain the selection and integration of the various technologies for wafer creation, I think the importance as a *Synthesiology* paper will become clearer.

Answer (Akiyoshi Chayahara)

In the wafer fabrication, unless there is some innovation in the cutting technology, there is no room for selection other than laser cutting and "direct wafer" technologies. In the case of laser cutting, about 1 mm width disappears as the reserve portion to cut diamond to 1 cm size. Even if we achieve high speed, the cost will be a problem at the current growth rate of 50 μm/h, and when over 1 inch is cut, reserve portion cannot be tolerated. Therefore, at this point, we believe the "direct wafer technology" is the most realistic and optimal manufacturing method. We hope the people of the processing fields will become aware that such issues are present, and propose an applicable cutting technology.

For mosaic wafer, we plan to continue the size increase of the single crystal by the repeated growth method, but at this point we do not have any ideas for further accelerating the size increase. In contrast, bonding is done in the lateral direction in the mosaic method, and is a method that matches well with the CVD that enables deposition on large surface area, and immediate size increase is possible. Also, if the defects are reduced in the crystal fragments, these can be "copied" and bonded, and the mosaic wafer, in principle, can be increased in terms of quality instantly. Therefore, we shall work on the mosaic technique as our immediate topic.

Investigation of the distribution of elements of the whole of Japan and their applications

— Geochemical map of land and sea of Japan —

Noboru Imai

[Translation from *Synthesiology*, Vol.3, No.4, p.281-291 (2010)]

A geochemical map of the whole of Japan has been drawn for the first time by surveying the distribution of elements in land and sea throughout Japan. This map revealed the natural background of the elements distribution and allows us to know the continuous flow of elements from land to sea. The samples used in this work are 3024 riverbed sediments and 4905 seabed sediments, and 53 elements including toxic elements of As, Hg, Cd, etc. have been analyzed. In this research, a new survey method has been established for a certain district at first and then it has been applied to the whole of Japan with modification taking realistic operability into consideration, and the object has been extended from land, sea to soil. The geochemical map is also used for evaluating the pollution of soils and marine sediments resulting from human and industrial activities. The results have been made public through publication and website and have had various social impacts. In this paper, the research scenario adopted to compose the geochemical map of Japan is first described, then a series of research processes are described starting from material sampling and treatment chemical analysis, measurement of element concentration, composition of geochemical map to data release.

Keywords : Geochemical map, distribution of elements, toxic elements, environmental pollution

1 Introduction

What elements exist in our surroundings and what are the concentrations of those elements? Such basic knowledge has not been understood until recently. And such knowledge has not been readily accessible. A geochemical map enables anyone to understand this valuable information visually at one view. For example, when discussing soil and marine pollution, which have become severe problems, such a tool will become a key to infer the distribution of toxic elements such as arsenic, mercury, and cadmium. This paper describes how the nationwide geochemical map in Japan was first planned, and then how it was actually made and used.

2 Background and purpose of the geochemical map

2.1 What is a geochemical map?

A geochemical map is a distribution map of elemental concentrations on the surface of Earth (surface of the Earth's crust). Figure 1 depicts what factors determine the distributions of elements. The most important of them is what kinds of rock and sediment are distributed in the region. This is a natural background. Additionally, influences from industrial, agricultural and urban life activities are important influences. The actual distributions of the elements constitute the sum of these various factors. In other words, for pollution, we should consider these factors in comparison with the natural background.

2.2 Purpose

The purposes of the geochemical map are mainly classifiable as two (Fig. 1). The first is to provide basic geochemical information about the land of Japan. Information about the distribution and movement of elements in the surface of the earth are basic data supporting all discussions related to earth science such as the origin of rock or the formation of the Japanese islands. That information is the basis for the research of earth sciences, which are undertaken to study what elements exist and where they are distributed. It is also important to know the regional elemental concentration or the average chemical composition of a larger area. For example, the average chemical composition of Japan is the most basic information, showing what elements make up the Japanese islands. Another example is the natural radiation dose, as estimated from the concentrations of uranium and thorium on the Earth's surface. As a scientific application, the geochemical map is used to estimate the natural background radiation dose using a liquid scintillation device (KamLAND) for neutrino measurements at Kamioka in Gifu Prefecture. Here, the dose is inferred from the concentrations of the uranium and thorium on the Earth's surface, as obtained from the geochemical map[1].

The second purpose is to address environmental problems. The geochemical map provides the key to clarification of the soil and marine pollution by industrial or factory wastes. To evaluate such pollution, it is important to obtain the natural background, which is then used as a baseline of pollution and the distribution of toxic elements. However, such an investigation has remained limited to small regions.

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No detailed or comprehensive investigation has yet been performed for the entire country of Japan. In this study, the distribution of 53 elements and their background concentrations including toxic trace elements (As, Be, Cd, Hg, Mo, Sb, etc.) in the land and sea of Japan were obtained through production of a geochemical map. We also investigated the geochemical behavior of elements and the origin of elements in the environment[2][3]. The geochemical map shows the nationwide distribution of elements and provides basic data to clarify the origin and the circulation mechanism of elements. It also offers basic data for the evaluation of the anthropogenic pollution in the environment, for the prevention of the spread of contamination, and for remediation planning.

3 Flow of geochemical mapping

Figure 2 depicts the scheme of the geochemical map. There are four steps that must be taken to produce the geochemical map: sample collection, sample treatment, chemical analysis to measure the concentrations of the elements, and map drawing using a geographic information system (GIS). First, the sampling position was determined by reference to existing geographical, geological, and soil maps in the laboratory. Then the samples were collected at selected points in the field. Samples were stream sediments, marine sediments, and soils collected from all over the country. After bringing the samples back to the laboratory, they were dried and sieved in the laboratory. If necessary, the magnetic minerals were separated or powdered. Then, the samples were decomposed with the mixed acids, and the concentrations of elements were measured using the ICP–AES, ICP–MS, and atomic absorption spectrometry. The geochemical map was drawn using GIS from the obtained elemental concentrations of respective samples. Photographs of sampling, the collected samples, the sample treatment, and the geochemical map for the stream sediments and the marine sediments are also portrayed in the figure. Regarding stream sediments, sampling was easy: one could go to the river and collect the samples. However, sample preparation required separation of the magnetic minerals after sieving and drying. For the collection of marine sediments, use of a ship was necessary. Samples were obtained by dropping the sampler to the sea floor. Collected samples were dried and powdered. Chemical analyses and map drawing were conducted similarly for all samples.

4 Development of research of geochemical mapping

The geochemical map was made to explore the mineral deposits to find local high concentration anomalies of heavy metals on the surface. However, in developed countries, few undiscovered deposits exist. The geochemical map is now of great interest from another perspective, as an illustration of environmental problems, because the map shows where and how toxic elements are distributed. In this respect, the British group of Webb in Imperial College formed a nationwide geochemical map for the first time in the world[4]. They produced a nationwide geochemical map by collecting about 50,000 samples gathered throughout the United Kingdom (about 151,000 km^2). It was designated as a Geochemical Atlas. At present, the geochemical map has been extended to encompass all European countries[5]. Please refer to references cited herein for more information about foreign and domestic geochemical maps[6]-[9].

4.1 Research scenarios at the National Institute of Advanced Industrial Science and Technology (AIST)

Figure 3 depicts the scenario for making and opening to

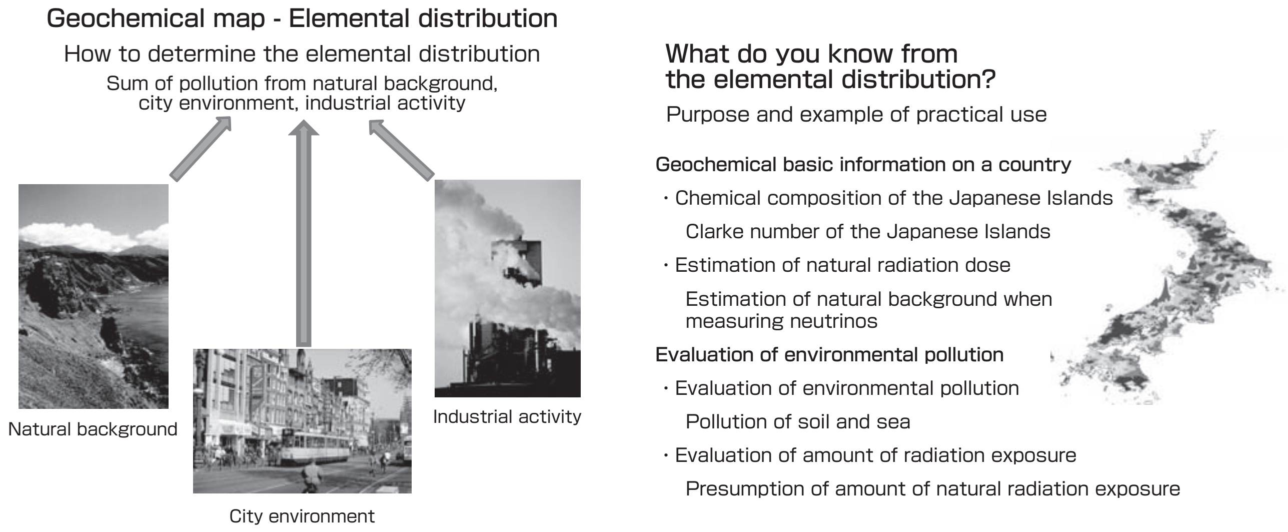

Fig. 1 Factors of elemental distributions in the geochemical map and an example of its practical use

The sum of the natural background and pollution of industrial activities and the city environment yields an element distribution. A geochemical map is used as basic geochemical information related to a country and for the evaluation of environmental pollution.

the public of the geochemical map of Japan. As factors affecting the production of a geochemical map, elemental distribution, elemental abundance, crust surface, kind of element, kind and collection density of sample, land or sea, representativeness of samples, processing of sample, chemical analysis, media to the public, drawing and standardization of data, system of research and analysis, standardization of method were considered, as shown in the figure. These basic factors for fabricating a geochemical map can be unified further as five components: basic characteristics, completeness, reliability, user convenience, and operability. Each of these components becomes a basis for the geochemical map. The final goal is the formation and public presentation of a geochemical map of all Japan, in which the sea and land maps are unified.

Figure 4 depicts the history of the geochemical map in AIST. It was the first time for us to produce a geochemical map systematically for the northern Kanto region, although the geochemical exploration to find mineral deposits had been conducted in AIST for a long time up to that time. The purpose of the project was the construction of techniques and methodology as a first step to our assessment of chemicals throughout the whole country. Then, the geochemical map of Sendai and Yamagata, and the coast of Sea of Japan (from Hokuriku to Akita) were made in respective projects. Subsequently, the geochemical map of land of the whole country was completed. As the next step, a nationwide geochemical map of the sea was fabricated as an extension of the land map. Then the nationwide geochemical map of land and sea was completed. At present, a nationwide geochemical map of soils is being developed as an additional resource.

4.1.1 Geochemical map of northern Kanto (Seeking to build and develop the methodology)

The Geological Survey of Japan (GSJ) compiled a geochemical map of the northern Kanto region from Mito to Iwaki in 1991, as described above[10][11]. The motivation for starting the project was the completion of the British geochemical map of the U.K., which was published and which subsequently caused a huge impact on studies there and abroad. The simplicity and strong impression of the map are noteworthy: any map user can survey the elemental distribution of the entire U.K. easily by color. The technique was geochemical exploration seeking ore deposits, which was the same goal as that pursued by the geochemistry group of GSJ up to that time. The project of geochemical map started as a large project with high expectations; all groups related to geochemistry cooperated to produce maps jointly at that time.

In the geochemical map of the northern Kanto region, 3850 stream sediment samples were collected from the area of about 4000 km^2 (the sampling density was one sample to about 1 km × 1 km). At the project's outset, it was an important problem that this huge number of samples had to be collected. Eventually, 7–8 researchers and more than 20 assistants (students) formed several teams. The samples were collected during the first two weeks of the summer

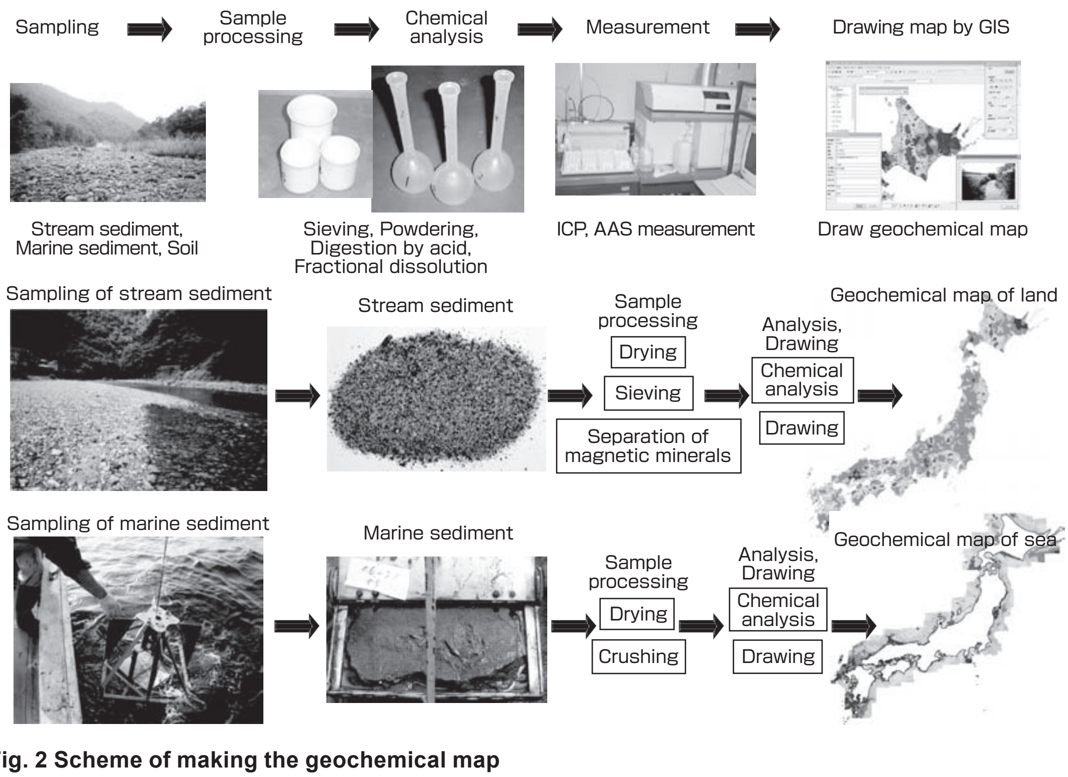

Fig. 2 Scheme of making the geochemical map

The figure shows the workflow from sampling to drawing the geochemical map by GIS, samples used for this study, stream sediments and marine sediments, sample treatments, chemical analysis, and drawing the geochemical map.

vacation over five years. At this time, the sample treatment was planned to be completed to the greatest extent possible in the field. The most important consideration was to finish the sieving and drying in the field. Fine-grained sands were separated by sieving them with river water. Then chemical analyses were conducted using ICP emission spectrometry. Thereafter, automated neutron activation-analysis was used to analyze many elements simultaneously. The analyzed elements were 26 elements such as cobalt, chromium, copper, nickel, phosphorus, lead, uranium, and zinc. This research

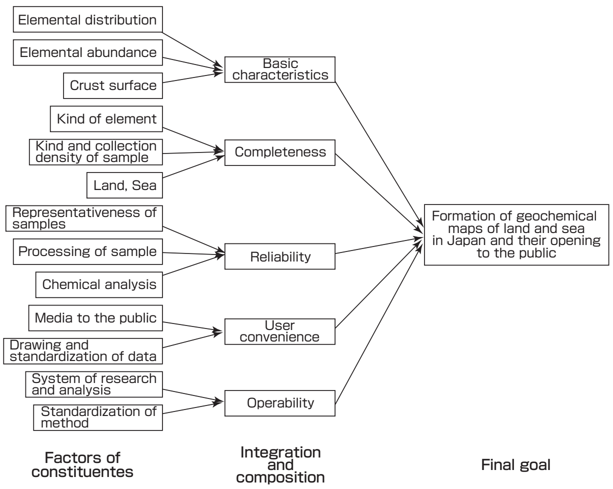

Fig. 3 Formation of the geochemical map of Japan and a scenario for opening access to the public
Components and key basic elements to support the geochemical map and the final goal

project was extremely important because the geochemical mapping of large areas was done for the first time in Japan. However, because it required a huge amount of work from sampling to analysis, it was important to allocate individual roles and to work appropriately.

4.1.2 Geochemical map of Japan (Development by converting the mode of thinking)

After the project of mapping the northern Kanto region, we sought to extend the area of the geochemical map to the whole country. However, because the same method in the northern Kanto region would have to be applied similarly, we were unable to continue the project. Because the area of Japan is about 380,000 km^2, the necessary number of samples would become 380,000 as 1×1 km mesh. Because such a huge amount of time and cost were deemed necessary to achieve the project, nobody would take the group's appeals seriously, even when proposed. Meanwhile, the work to produce the geochemical map around Sendai[12] and Yamagata City[13] was continued, although the area was quite small. As the sea area, the geochemical map was also formed in the coastal area from the Noto Peninsula to the seas off Akita[14].

The major turning point came from a discussion on the topic of whether a nationwide geochemical map was truly impossible. Although it seemed infeasible because the project needed funding and staff on an enormous scale, it was suggested that the mode of thinking should be reversed. First

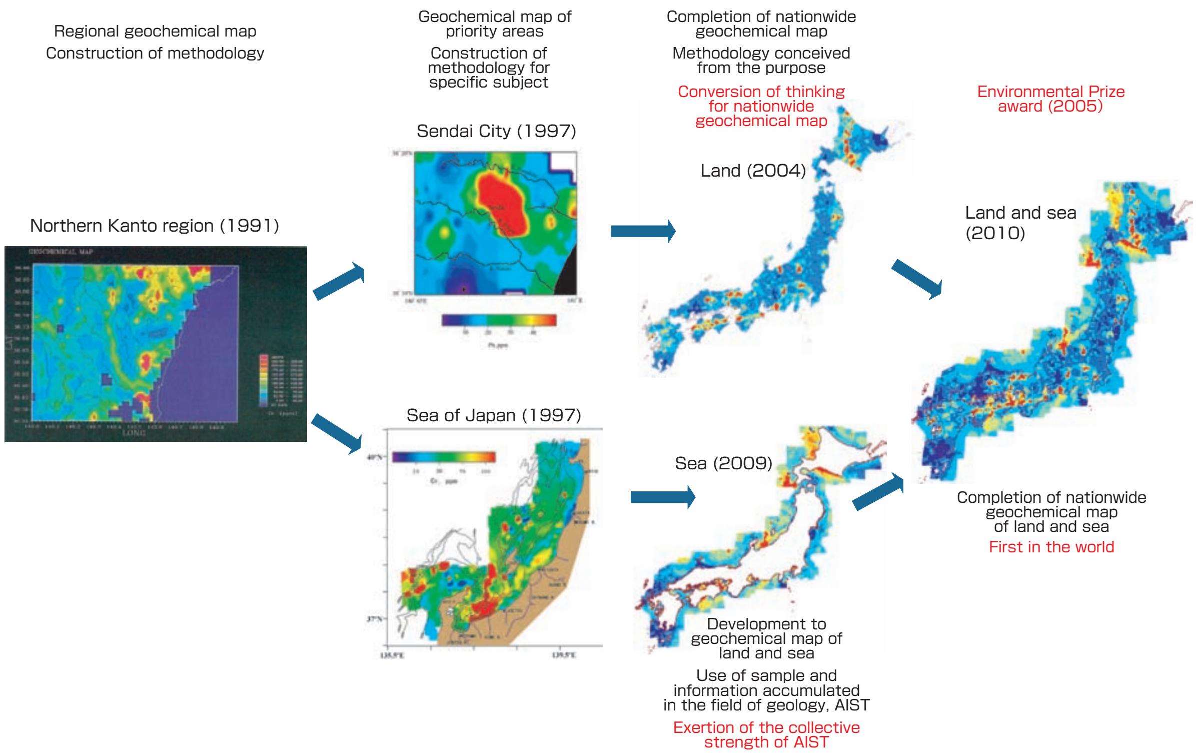

Fig. 4 Development of research in producing a geochemical map
From the geochemical map of the northern Kanto region (1991) to a geochemical map of the land and sea

such costs and staff should be estimated as necessary from a realistic viewpoint to compile such a nationwide geochemical map. At that time, the sample collection density of 1 km mesh was thought to be primarily important, and a coarser density was not meaningful. However, if the coarser mesh were adopted, then a possible plan could be formulated in terms of cost, the number of workers, and the period needed for the project. The period of the plan of the project was set as five years, and the number of samples was suppressed to about 3000 by setting the mesh to 10 km. Consequently, the nationwide geochemical map plan became a feasible one by adoption of the sample number and mesh.

At the first step, the geochemical map was to cover the whole country first, even with coarse sampling density. Thereafter, as necessary, the density was expected to be raised separately for specific areas of interest. In this way, both demands of covering the whole country and scientific significance would eventually be fulfilled. The budget was obtained from the Environment Agency, and the project was begun in 1999. The first geochemical map of the whole country of Japan was therefore completed in 2004[2]. Several features of elemental distribution in the Japanese archipelago were clarified for the first time in spite of the coarse mesh of 10 km that was chosen. Results show that it is not necessary to worry about the overly coarse sample collection density to understand anything. Fortunately, the nationwide geochemical map of Japan has attracted much social and scientific interest because of its ease of visual comprehension. It has been used in various fields. The project team won the “Environmental Prize” in 2005[15].

4.1.3 Geochemical map of the sea (Progress to the next stage)

Several ideas of how to advance the research of geochemical map to the next step were then raised. Another possible project was the elemental distribution for land extending into the sea. Geochemical mapping of sea areas off the coast of Hokuriku to Akita had been done before. The GSJ has studied the sea around Japan for many years, and many previously collected sea bottom sediments have been analyzed. For the geochemical map of the sea of the whole country, we can use those prior collected samples accumulated by GSJ. In our project, the bottom sea sediments were newly collected in the sea where no samples had existed before (about 30 percent of the whole country). Consequently, all marine sediments in the sea of the whole country could be collected. The total old and new samples were 4905. The geochemical map of the land and sea of the whole country was completed using these samples in 2010[3]. The nationwide geochemical map of both land and sea was the first of its kind in the world. The elemental distributions between land and sea were thus connected, which enabled us to elucidate the movement of elements from land to sea. A soil geochemical map of the whole country is being made at present as development of further study by collecting about 3000 soil samples throughout the country.

5 Factors of technology to produce a geochemical map (Development of technologies for objectives)

Factors of technology that are useful for producing a geochemical map include sample collection, chemical analysis, and map drawing. To achieve the objectives, the actual techniques to produce geochemical map are described to notify users of differences from the conventional method. For a detailed description of the procedures, refer to the past reports of the literature[2][3]. The important considerations are the automation of handling vastly numerous samples and the standardization of processes for all samples using a single technique. Because the geochemical maps had been made using different techniques in various regions, it was difficult to compare them quickly. However, by adopting standardized techniques, data of the whole country can now be analyzed systematically in a unified manner.

5.1 Sample collection

5.1.1 Geochemical map of the northern Kanto region[11]

In making the geochemical map of a large area, how we collect numerous samples is the most important consideration. The initial method used for collection of stream sediments in this study was how to reduce the sample processing time after sampling. Therefore, we tried to finish the necessary work such as sieving to the greatest degree possible in the field. Actually, one researcher and 2–3 assistants (students) constituted one team, which moved to the sampling position by car in checking 1/25,000 or 1/50,000 geographical maps. It was necessary to move to small rivers for sampling in cases of the geochemical map of 1 km mesh. If unable to reach it by car, it was necessary to walk to the sampling area. The sampling position was determined principally as the end of the branch of a river (the most downstream reaches of the watershed). The sampling point was determined beforehand in the laboratory, and how we could reach the area quickly was important.

After arriving at the sites, the teams separated stream sediments finer than 80 mesh (about 0.17 mm) by sieving. Stream sediments were put on the sieve of 80 mesh, and the sand and mud of 80 mesh or less which passed through the sieve were separated using filter paper by pouring the river water. However, some samples took a very long time for filtration because the filter paper became clogged, or it took much time in searching the sands of minute grains because we were sometimes unable to find them where the flow of the river was fast. If the required amount of the sample was not taken, then the filtration was repeated, which took much more time. After that painstaking process, often only several samples were collected in a day. The samples were brought to a hotel by the team and laid out to dry. They almost always dried completely overnight. In this way, about 60–100 samples per person were collected during trips conducted over two weeks, and 600–800 samples were collected overall.

5.1.2 Geochemical map of the whole country[2]

When the geochemical map of the whole country was being made, reducing the human load for work in handling vastly numerous samples was the most important problem, as we had learned when producing the geochemical map of the northern Kanto region. If all the sampling work were outsourced, then the necessary time and effort for us would have decreased. However, the cost would become too enormous to realize it as a normal research project. To save costs, the samples were to be collected by ourselves to the greatest extent possible. It was also important that the time-consuming sampling process be simplified. For that reason, work such as filtering was not performed in the field and no other work than collecting the sample was conducted. In this way, the costs were reduced, even if the work was outsourced. Consequently, the drying and sieving were not conducted in the field as in the case of the northern Kanto region map compilation. Fine-grained sand of about 2 kg was sampled using a shovel or bottom sampler. Moreover, the sampling point was set to the place where a large river intersected a large road: a location that could be reached easily. However, it took much time to move to the next sampling site because the sampling density was coarse and the distance separating sampling points was great. Especially for deep valleys in mountainous areas, even if it was apparently possible to collect a sample easily when viewed on a map, the actual river was often far under a cliff. Even in such cases, there was usually a small path running down to the river for use by sport anglers. Nevertheless, the sampling was sometimes impossible depending on the circumstances of the field. Eventually, about half of the total of 3024 samples were collected by ourselves. Otherwise, samples were taken by outsourcing. In all cases, dryness and sieving were done separately in a laboratory. However, the sample processing was efficient because the process allowed preparation of many samples at one time.

5.1.3 Sampling of sea-bottom sediments[3]

The most daunting problem was sampling to produce the geochemical map of the sea. The marine sediments were necessarily collected using a ship. Therefore, it was much too difficult to do ourselves, unlike the sample collection that was conducted on land. Especially, when the depth was more than several hundreds of meters, sample collection was impossible without a large specialized ship. It also entailed huge costs. We were able to reduce the costs greatly using marine sediment samples that the GSJ had collected in the past. In the survey, a marine research vessel of more than 2000 t was used for the surrounding seas of Japan whose depth was up to about 3000 m. For this study, the samples were newly collected in the sea for which we had no sample. Because the project had tight budget limitations, the depth of the seas in which we could collect the samples was at most 100–200 m. However, the areas with seas less than 200 m deep were sufficiently wide to constitute a good sampling area, especially in the west of Japan, where the continental shelf is developed well. There we were able to cover the large area of the sea easily. The marine sediment samples were collected using a glove bottom sampler (Smith–Macintyre type bottom sampler) that was installed on the survey ship. Sample processing was done fundamentally in the same way as for the samples from the land. The marine samples were 4905. Figure 2 depicts how the collected samples were raised from the sea bottom.

5.2 Chemical analysis

In this study, because it was necessary to analyze numerous samples, sample processing and analysis were automated and standardized as much as possible. In the geochemical map of the northern Kanto region, 26 elements were analyzed using ICP emission spectrometry and neutron activation analysis. For the geochemical map of the whole country, 53 elements were measured using ICP mass spectrometry and atomic absorption spectrometry. In both cases, an auto-sampler and automated measurement systems were used to the greatest extent possible. To simplify the sample treatment, stream sediments of less than 80 mesh were analyzed without powdering. In most cases, the analytical results obtained for samples that had not been powdered were the same as those obtained for powdered samples. Moreover, the stream sediment was analyzed after extracting magnetic minerals such as iron sands using a magnet. Heavy minerals are sometimes concentrated by the fractionation of river water. The purpose of extracting magnetic minerals is to avoid letting the map become an unnatural geochemical map. Especially in regions where many iron sands exist, the geochemical map becomes an *iron sand map*. Samples were decomposed using mixed acids of nitric acid, perchloric acid, hydrofluoric acid, and 0.1N hydrochloric acid.

5.3 Drawing of the geochemical map

In drawing a continuous geochemical map from geographically discrete sampling points, it is necessary to interpolate in areas for which data do not exist. The watershed analysis was made by GIS to determine the upper watershed area for each sampling point of stream sediment. The elemental concentration for each area is assumed to be the same. To simplify the calculation, the watershed area was converted to square mesh and the concentration data were allocated as the same value to each mesh. Then the geochemical map was drawn by interpolating the mesh data. In this study, the geochemical map was made without consideration of the movement of the marine sediment by seawater or the oceanic current because a more realistic portrayal quickly became too complicated to calculate.

6 Geochemical map of Japan and its implications (Behaviors of elements in nature and in human activities)

This study produced geochemical maps showing distributions of 53 elements in sea and land areas. It is necessary to interpret each elemental behavior according to its circumstances because its behaviors in nature and in human activities might differ from those of other elements. Here, we describe geochemical maps of chromium and mercury, which have characteristic features in terms of their respective distributions. Please refer to individual reports in the literature for details related to other elements and features of elemental distribution in respective regions[16]-[20].

6.1 Geochemical map of chromium (Cr)

Figure 5-1 shows the geochemical map for chromium. The two red lines in Hokkaido and Shikoku (areas of high Cr concentration) in this figure are noticeable first. A remarkable high-Cr concentration region of more than 200 ppm exists along the median tectonic line. The tectonic line crosses from west to east of the Shikoku and Kinki regions, reaches the Tokai and Kanto regions and another crosses the center part from north to south in Hokkaido. This prevalence is thought to result from the green rocks and ultra-basic rocks distributed along these regions that contain chromium and nickel in very high concentrations. The red area of high concentration in the sea is apparent in the coastal areas of off southern Hokkaido and Hokuriku. The most remarkable area is along the Hime River in Itoigawa, where the northern end of the Fossa Magna in Hokuriku District is located. The high concentration region of chromium on land extends to the sea. A high concentration region of chromium along the Hime River on land continues to the deep sea valley. Therefore, the detritus of the serpentine, which contains chromium in high concentration moves from the Hime River to the Toyama deep sea valley in the sea. This figure also portrays the topography of the seabed in this region. It is readily apparent that a deep sea valley exists in the north of Hime River and that the sediment flows from the Hime River along this valley to the sea.

6.2 Geochemical map of mercury (Hg)

Figure 5-2 shows the geochemical map of mercury. The mercury concentration is remarkably high in the region where large-scale mercury deposits such as Itomuka mine in Hokkaido and Yamato mine on the Kii Peninsula exist. Furthermore, the concentration of mercury is high around big cities such as Tokyo and Osaka on the land, and concentrations are high in Tokyo Bay, Ise Bay, and Osaka Bay. This prevalence is affected by anthropogenic influences from cities with large populations. This figure also shows geochemical maps of Kyushu, Hokuriku, and Kinki regions. The high concentrations of mercury off the coast of Niigata and in the Yatsushiro Sea and western Kyushu are visible in the figure. It is possible that the influence of the past mercury pollution remains in these high-concentration regions. The high concentration of mercury in the northern sea around Sado is considered to reflect the influence of the Sado gold mine in the past. The high concentrations of mercury in Ise Bay and Osaka Bay in the Kinki region are thought to be influenced by large-scale Yamato mercury deposits in the Kii

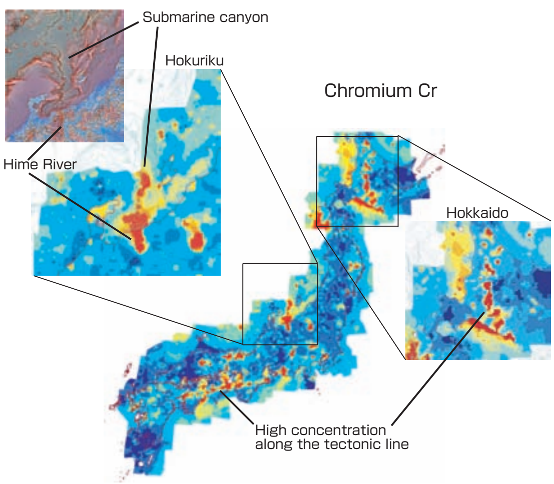

Fig. 5-1 Geochemical map of chromium (Cr) of Japan, Hokuriku and Hokkaido regions

A high Cr concentration region is apparent along the median tectonic line and the tectonic line in the center of Hokkaido. The high concentration region extends from Hime River to the sea.

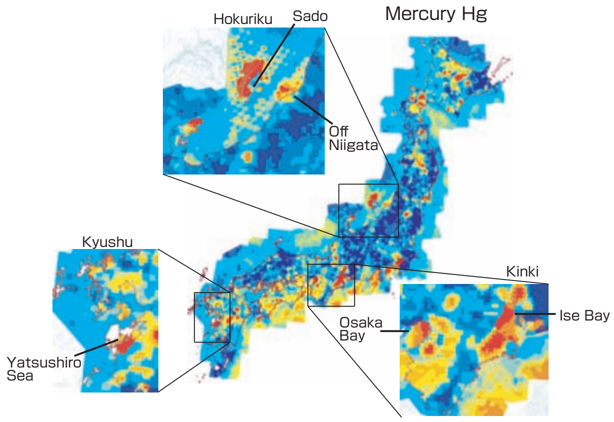

Fig. 5-2 Geochemical map of mercury (Hg) of Japan, Kyushu, Hokuriku, Kinki regions

High Hg concentrations off the coast of Niigata and in the Yatsushiro Sea reflect the influence of past mercury pollution. That in the sea off northern Sado reflects the influence from gold mines in the past. The high concentrations in Tokyo Bay, Ise Bay, and Osaka Bay are attributable to anthropogenic influences from the nearby large cities.

Fig. 5 Elucidating elemental behavior in nature and human activities using a geochemical map

Peninsula, in addition to anthropogenic influences from the large cities nearby.

7 Disclosing data to the public (Providing information to society as a public good)

A geochemical map homepage was made, presenting data of the geochemical map which had been accumulated. It was then made available to the public for easy access and reference on the web. Figure 6 shows the geochemical map homepage. The geochemical map of land and sea of the whole country is visible here, as are the regional geochemical maps and detailed information of each elemental concentration for all 3024 stream sediments and 4905 marine sediments. All of that information can be accessed easily on the network. Moreover, a photograph of the sampling point and the sample are displayed for all stream sediments. Photographs of the samples are available for some bottom sea sediments. Especially, a photograph of stream sediment can be enlarged by clicking, and the kind of rock and sediment distributed in the region can be investigated. In addition, the elemental concentration and the latitude and longitude of all the samples, the geochemical map of the whole country and regional map (the raster map / GIS shape file), and related information are downloadable from the website.

8 Practical use of a geochemical map (Various uses of the basic information of the nation)

The geochemical map presents the elemental distribution on the surface of the earth's crust for land and sea areas. The data are important as basic information of the entire nation. In addition, because stream sediments were collected from throughout the country and because the individual stream sediments represent their local watersheds, the average concentration of all the samples can be considered as an average chemical composition of Japan. The average chemical composition of Japan (Clarke number of the Japanese archipelago)[21], as calculated from a distribution ratio and the composition of typical 166 rock samples distributed in Japan is desired. This is considered to be a theoretical value, although the mean value of 3024 stream sediments in the geochemical map is a value that was actually measured in the field. It was clarified in this study that both values agree very well.

A geochemical map can also be used for evaluation of natural radiation doses, as determined by the sum of the natural radiations from surrounding rocks and sediments and the cosmic rays. The former is calculable roughly from the contents of potassium, uranium, and thorium in rocks and sediments obtained from the geochemical map. For instance, the natural radiation dose is known to be large in west Japan, where granite that contains much potassium, uranium, and thorium is widely distributed. The contamination levels of radioactivity from nuclear facilities in various regions can be evaluated through comparison with the natural background level.

For social purposes, the geochemical map is used as basic data for the evaluation of soil pollution. The concentration of elements is readily apparent from the map in the

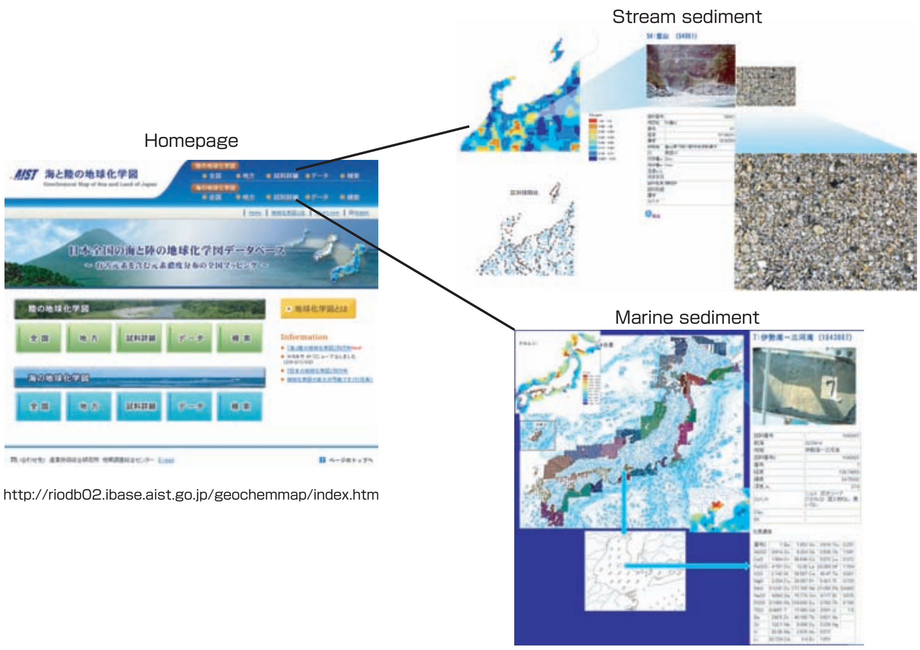

Fig. 6 Homepage of geochemical map
The homepage of the geochemical map (http://riodb02.ibase.aist.go.jp/geochemmap/index.htm) and detailed information of individual stream and marine sediments are shown. Photographs of sampling points and samples of stream sediment and marine sediment, the elemental concentration and the latitude and longitude of all the samples are shown.

facilities of municipalities and plants of companies. It is very effective as a preliminary check for additional detailed surveys of pollution. As described previously in 2.1, it is important to compare the measured concentrations with natural background levels. Then the environmental base line level can be known when the soil pollution is examined. If there are mineral deposits or hot springs in surrounding areas which have high natural background levels of elements, then it is necessary to distinguish anthropogenic pollution from these natural factors. Because the geochemical map represents the natural background level, the environmental pollution can be evaluated through comparison with the map as background. Such data are useful as base data to prevent the spread of pollution locally and nationally, and to produce appropriate policies of pollution control and remediation. A risk assessment of the location of a factory using a geochemical map enables us to reduce soil pollution assessment costs.

As described above, because all data of the geochemical map are fundamentally open to the public, various users propose different uses that we had not considered. For example, a joint research project with the Institute of Police Science was made to study the possibility of identifying the sources of soil using the database of the geochemical map of the whole country at present. We also hope that the data of the geochemical map will be useful for other socially beneficial tasks in the future.

Currently, we are compiling a soil geochemical map using about 3000 soil samples collected from throughout the country. We will apply a geochemical map to elucidate the distribution and the diffusion processes of elements in crust's surface, and will develop an evaluation system of toxic elements for environmental pollution that incorporates land, river, and sea areas. We also want to integrate various data such as those related to geology, geography, pollution, and social data to investigate environmental pollution in the future.

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Completed the doctoral course in Chemistry at the Graduate School of Science, The University of Tokyo in 1980, earning a Ph.D. (Science). Joined the Geological Survey of Japan, Agency of Industrial Science and Technology (current AIST) in 1981. Became the group leader of the Geochemistry Group, Institute of Geology and Geoinformation. Engaged in research of the geochemistry of rocks and sediments, ESR dating, geochemical map, and geochemical standard reference materials. For this study, was in charge of the geochemical map of the land and sea in Japan. Awarded the Environmental Prize for the geochemical map in 2005, and a Prize of the Minister of Education, Culture, Sports, Science and Technology for a certified reference material in 2010.

Discussions with Reviewers

1 General comments

Comment (Shigeko Togashi, Evaluation Department, AIST)

This paper is meaningful for the methodology to complete the geochemical map of land and coast of Japan as one of the basic geological information of the country. By converting the conception, the geochemical map covered the whole country by acquiring external budget although it started from the regional map of small areas. Especially, it is noted that an Environmental Prize was awarded for the widely used geochemical map in society. This paper therefore is suitable for publication in *Synthesiology*.

As described in this paper, it is better to show first what the geochemical map is and how it is used for the reader by using figures which are easy to understand. Please indicate the keywords of some concrete examples also from the practical use of the later chapter. In addition, for the history of geochemical mapping in AIST the description of the methodology should be more generalized as a method of synthesiology. Although the original manuscript was “just explanation”, the manuscript which was reconstructed by generalizing the approach of research and the methodology of the social contribution has been much improved by corresponding to the above-mentioned primary comment.

Answer (Noboru Imai)

According to the reviewer’s comment, the structure of the text was changed to clarify the thrust of the discussion. The geochemical map is explained in “2.1 Background of the geochemical map”, and the scheme of the geochemical map is described in “3. Flow of geochemical mapping”. The configuration of the entire text was modified.

2 Similarity of research scenarios

Comment (Akira Ono, AIST)

The target of this research is making the geochemical map of Japan which covers both the sea and land. The result is not only original but also excellent as the *Type 2 Basic Research* and *Product Realization Research* using the integration and synthetic methods.

Making the geochemical map is considered to be comparable with making a large-scale database. I have an experience to build a database of physical properties, and think that the setting a scenario seems to be analogous to that of geochemical map.

Fundamental qualities of the database are composed of the characteristics of data, coverage and reliability of data, convenience in the use, and operability in making and using the database. I think these qualities of the database are also common to the geochemical map. If you agree with this, please draw an analogous scenario for the geochemical map, which I think will make it easier for the reader to understand.

Answer (Noboru Imai)

Thank you for reviewing the manuscript so carefully and thoughtfully. I also very much appreciate your suggesting a figure of the concrete scenario. The figure is intelligible in allowing a purview of the whole work. Several terms were corrected based on this suggestion; the scenario is depicted in Fig. 3. The viewpoint outside of this specialty has been particularly helpful for me to understand the work more comprehensively.

3 Motivation at an early stage of the research

Question (Akira Ono)

As described in this paper, the origin of a geochemical map of Japan goes back to that of the northern Kanto region developed in 1991. After that it took 20 years to publish the geochemical map of Japan. I think that the methodology which was developed in making the geochemical map of the northern Kanto region led to today’s success.

In that sense, I think that it was a very important point that you decided to start the work of the geochemical map of the northern Kanto region. What was the motivation that made you decide to start it then? Did you start it because you were inspired by the British geochemical map research in advance, or because of your own academic interest?

Answer (Noboru Imai)

It was a very important point that the geochemical map of the northern Kanto region was first launched as you pointed out. I think that there were several purposes for starting the geochemical map project at that time. The geochemical map of the northern Kanto region was completed in March 1991. The five-year project was started on April 1, 1985. Therefore, we had actually prepared the project from 1984 because the budget had passed in the prior year. At that time, because I had just started my career as a researcher, I did not know all the circumstances surrounding the start-up of the project. However, I think it occurred as follows.

The first motivation of the start-up of the project was the British geochemical map, which made a big impression on many people, as you pointed out. The ease of understanding the distribution of elements in the UK at a glance gave us a strong impression. Moreover, the used methodology was exactly the same as that for geochemical exploration to find mineral deposits, which was the method used by the geochemistry group in GSJ. Therefore, it seemed to us that we could undertake the project without delay.

The research groups involved in the geochemical map then were doing basic research in geochemistry and doing chemical analyses of geological materials. They had been working somehow far from the main stream of making “the geological map” in GSJ. The geochemical map work started as a big project necessitating the cooperation of several geochemistry groups to produce the map collaboratively. Therefore, we harbored great expectations for its progress as a first project for the geochemistry groups. A unique scientific interest was also involved: to know the distribution and the movement of elements in the earth's crust. However, the promotion of geochemical study by introduction of large-scale equipment such as neutron activation analysis and ICP emission analysis was another major purpose. I think everyone certainly appreciated the project after the nationwide geochemical map was completed.

4 Similarity of the methodology between field research and laboratory experiment

Question (Akira Ono)

In viewpoint of the amount of data, the sampling points at a finer interval and the coverage of a wider area are in tradeoff. Which you should give priority to and how you harmonize them may be hard problems. In this work, it may have been an important point for you to assume first that even coarse sampling was scientifically meaningful if the coverage was wide enough, (which was excellently revealed later).

Suppose a laboratory experiment where we measure a physical property of a sample changing the sample temperature in a range. It is recommended that measurements are made firstly over the whole range of temperature at a coarse temperature interval to see quickly the overall trend. Then measurements follow at a finer temperature interval in selected ranges of interest. I think that the technique of understanding the whole image first and proceeding toward detailed parts is a common approach, which is very effective even if the field of research is different. Unlike the laboratory experiment, because the field research cannot be repeated easily, such a technique is thought to be more important.

Answer (Noboru Imai)

I think that the technique of understanding the whole image first and proceeding toward detailed parts is important, as you have pointed out. As for the question about why we did not notice that point earlier, because similar research projects including those of foreign countries had adopted the mesh size of 1 km, we did not consider trying a more coarse mesh to cover the whole country. Considering that there are various types of mountains, valleys and plains, a mesh size of 10 km seemed to be too coarse to obtain useful data from geographical and geological viewpoints. I did not realize at that time that excellent geochemical maps could be obtained with such a coarse mesh size.

We first thought that regional geochemical maps made by the local governments and universities in individual prefectures should be connected to cover the whole country. However, this did not progress very easily, and small-scale geochemical maps are now being made at a university to which the proposer of the first project moved, and at other universities which have an interest in compiling and contributing local geochemical maps.

5 Representativeness of samples

Question (Akira Ono)

In this research, the stream sediment at the root of a branch of a river is assumed to represent the area of watersheds of the branch. I think this is a very good idea. However, how did you check the assumption that the stream sediment fully represents the watersheds? Please tell us of any other thoughts concerning representativeness of analytical results, for example other conditions that might be needed.

As you mentioned about the element distribution in soil in your manuscript, what is the difference of the definition between surface of the crust and soil? I imagine as an amateur that soil is mixed in the stream sediment at the root of a branch of a river. Is the mixing of soil in the sediment negligible?

Although the element distribution in soil is not the main subject in this paper, can you tell us where you should sample the soil so that the sampled soil represents a certain area?

Answer (Noboru Imai)

It was confirmed in several places that the stream sediment at locations in the watersheds of the rivers represent its whole watershed. The examples of zinc and phosphorus concentrations in Sendai City are shown as follows. In Fig. a, the 39th sample, which is taken at the root of the Hirose River, is thought to be a representative point in the entire watershed of the Hirose River. Figure b shows that the averages of the concentrations of both zinc and phosphorus for all samples in the watershed agree well with the concentration of the 39th sample. Therefore, in this case, the entire watershed of the Hirose River is well represented by sample No. 39.

To improve the representativeness, the sampling site is carefully selected to facilitate collection of samples that are as fine as possible. In addition, samples which are thought to be influenced by human activities such as industrial wastewater or enrichment of heavy minerals such as of iron sand should be avoided carefully.

Regarding the difference of the definition between the earth's crust surface and the soil, the thickness of the earth's crust is several kilometers on land and several tens of kilometers in the sea. The definition of the word "surface crust" is ambiguous. Nevertheless, I think the thickness is within 1 km, from several tens to hundreds of meters. The soils are composed from the surface organic layer to A, B, C horizons in sequence proceeding to greater depths. The thickness is from a few centimeters to several tens of centimeters (several meters). The ratios of the soil in stream sediments differ greatly from place to place, but the ratio is not so large because the soil thickness is sufficiently small compared with the surface crust, although the surface materials are mainly incorporated into stream sediment. After all, because the soil is fundamentally the product of the surrounding rocks and sediments by erosion, the chemical composition of the soil does not differ much from that of rocks and sediments, although there are various additional anthropogenic influences from external contamination.

Regarding the sampling method, the sampling point density is determined from the number of samples and the area. In this

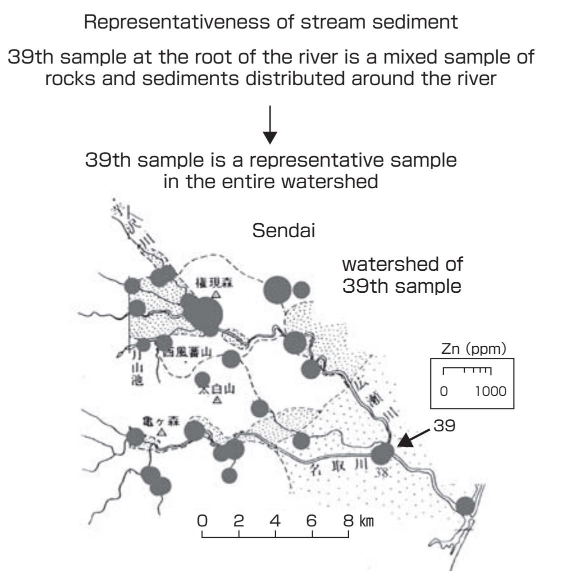

Fig. a Zinc and phosphorus concentrations in Sendai City

study, it was about 10 km mesh. Therefore, one sample was collected from every 10 × 10 km area. The sampling density was so coarse that the sampling points were determined carefully, and they should represent a wide area in producing a nationwide map. Actually, while we referred to and compared the geological and the soil maps, the sampling points were determined so that the points represent the geological and soil divisions of each area. Results show that the geochemical map using the stream sediments agrees well with that using the soil. However, when we can take a higher sampling density, the soil is basically collected in an exact grid.

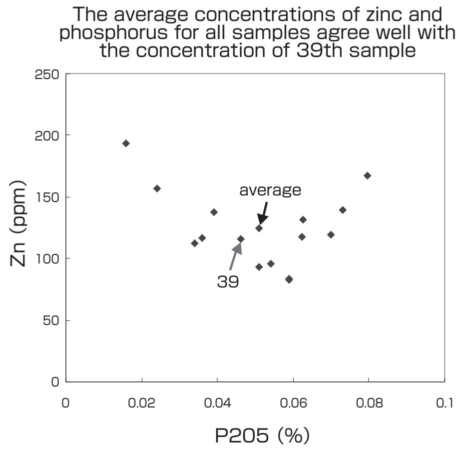

Fig. b Scatter plot

6 Sample storage and future study

Question (Akira Ono)

In the investigation of marine sediments, it is written that the samples collected by AIST in the past were used for the chemical analysis in this study. This indicates satisfactorily the continuity, integrity, and mutual availability of research which reflect the excellent function and system of the AIST organization.

Are the samples as well as those newly collected in your project in land and sea stored in Geological Museum for the use in which more detailed analysis will be needed in the future?

Answer (Noboru Imai)

The researchers and persons in charge of the GSJ project of collecting bottom sea sediment in the marginal sea in Japan also joined our project of the geochemical map for the collection of the marine sediment. Therefore, we were able to use a huge number of sediment samples collected in the past, and in this study by collecting the new samples in areas for which there were no samples, we were able to obtain a full set of sediments for areas throughout Japan. Therefore, we were also able to contribute much to their project of marginal sea mapping and assessment.

About 3,000 stream sediments, 5,000 bottom sea sediments, and 3,000 soils collected in the geochemical map project are stored and classified to be used anytime. That inventory is extremely valuable property for which the samples whose chemical composition is known are kept to be used as a set for the whole country. The samples have been used by outside researchers to date for making a national soil database of the Institute of Police Science and for producing a national map of a strontium isotopic ratio at Nagoya University. Principally, the geological samples were kept in the Geological Museum. The samples collected through the geochemical map project are also kept in the Geological Museum, as you have pointed out.

How car navigation systems have been put into practical use

— Development management and commercialization process —

Hirosaka Ikeda[1]*, Yoshinobu Kobayashi[2] and Kazuo Hirano[3]

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Japanese manufacturers have played key roles in developing practical vehicle navigation systems (hereinafter "NAVS"). The NAVS have spread throughout the world and have become extremely useful. The market size in Japan alone is considered to exceed 5 hundred billion yen a year. This system could not have been achieved without the development of a scheme to create a nationwide digital road map, subsequent map creation, methodology to provide traffic information to vehicles, GPS development and its utilization in the United States. Much effort has been directed toward laying down infrastructure comprising these factors. Furthermore, it has been also necessary to develop the required software and hardware for the NAVS including location detection techniques such as map-matching, gyro sensors, displays, memory and microprocessors. The NAVS are presently evolving as onboard information communication systems. This paper describes their development and commercialization, which started even before the requisites for the NAVS developed fully, from a development management perspective.

Keywords : Car navigation system, map database, map-matching, gyro sensor, route guidance, VICS, GPS

1 Introduction

In recent years, many automobiles come with a NAVS as a standard feature, even in rental cars and taxis. One of the authors stayed in Germany four years ago and could drive in unfamiliar areas at will without using a map book, because the car he drove had a NAVS. The author did not see a turn-by-turn system simply indicating the next direction on the display, which European engineers had advocated at first. Instead, all the NAVS units were Japanese-style map navigation systems.

The very first navigation system was the south pointing chariot said to be invented by the Yellow Emperor of Yin as related in the *Abridged Eighteen Histories* of China. Centuries later, Honda created a NAVS using a gas rate gyro in 1981. It incorporated a map on a transparent sheet and projected the vehicle's location onto the sheet[1]. Honda's NAVS was followed by some subsequent devices that indicated the route to take based on terrestrial magnetic field. The contemporary NAVS began when Toyota mounted a unit on the Crown that indicated the vehicle's location on a map shown on a display device. This NAVS calculated the cumulative moving distance based on the magnetic field and on a speed sensor output. Although the vehicle location calculated by this NAVS gradually deviated from the true location, this system sparked off a trend towards vehicles provided with NAVS. Toyota's system used a small-scale 1:50000 map (1 cm on the map being equal to 500 m on the ground). In 1989, a NAVS developed by Sumitomo Electric was mounted on the Nissan Cima. This can be said to represent the first practical NAVS in that it displayed the vehicle location on a road map. This paper reviews the NAVS research and development process at Sumitomo Electric and explains key points and difficulties in making a NAVS practical.

2 Road information digitization technology as the foundation for NAVS

The NAVS is a system that displays your vehicle location on a map, suggests a route that leads to your destination along roads on the map, and displays traffic jam conditions. Therefore, to create the complete system, the onboard equipment itself is not sufficient without the development of information technology as part of the road infrastructure. Notably, Japan developed that infrastructure early on.

In Ginza, Tokyo in 1966, traffic management system demonstration tests were conducted, connecting traffic signals and vehicle detectors online and using a computer to detect the traffic and controlling traffic signals[2]. The system proved itself to be effective and was put into practical use. The challenge was to find a way to prevent the rapid increase in traffic accidents and ease traffic jams. In 1973, the then Ministry of International Trade and Industry conducted an experiment using the Comprehensive Automobile Traffic Control System[3] (CACS). In this test, coils were installed under the road at intersections, and as vehicles passed through intersections they received guidance radio waves and routes were displayed on onboard equipment to avoid

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traffic jams. To make the system practical, it was necessary to provide both onboard equipment and an infrastructure. The system was not practical, with development caught in the dilemma of chicken and eggs. However, its usefulness was proven in guiding vehicles to uncrowded roads using traffic information.

Aside from this, the National Police Agency was promoting a patrol car location system[4] (car locator in police terminology) development project to enable the control center to recognize locations of patrol cars and guide them so that the patrol cars could be deployed efficiently.

In these circumstances, already involved in road infrastructure technology, Sumitomo Electric felt the need to develop a NAVS. In 1983, having taken the initiative in traffic management and CACS projects at Sumitomo Electric, Nobuo Yumoto (later Senior Managing Director) found map-matching that was being developed in the US, and realized if it could be incorporated into the NAVS, the system could be made practical. He then began developing a NAVS employing the map-matching system.

Subsequently, the government and the private sector collaborated to develop the technology for the Road and Automobile Information System. In 1984, the Road / Automobile Communication System (RACS) started operation and in 1987, the Advanced Mobile and Traffic Information Communication System (AMTICS) commenced. These systems facilitated acquisition of vehicle information. Meanwhile the NAVS began to be installed in vehicles. There was a growing trend toward introducing a new vehicle information system for mobile units. Consequently, existing members of AMTICS and RACS plus new members established Vehicle Information and Communication System (VICS) in 1991, which later evolved into the Intelligent Transportation System (ITS).

3 Navigation system development

In its development of the NAVS, which consisted of an onboard NAVS and a patrol car locator, Sumitomo Electric developed common technology and parts for both. This report focuses on the NAVS.

3.1 Current location detection technologies

(1) Technological development of map-matching[5]

The basic technologies for the NAVS are: location detection to determine where the vehicle is, and route computation to calculate the route to the destination and guidance to guide the vehicle along the route.

Location detection, one of the basic technologies, is relatively easy using the GPS satellite-based system. In the early days of our development of the patrol car locator and NAVS, there existed only a few GPS satellites. Moreover, the GPS satellites were still under construction and were not fully usable, being available for only one to two hours a day for location calculations.

1) Development of map-matching

In principle it is possible to identify the current location if the original location, driving distance from that location and driving directions are known. This method is known as dead reckoning. One critical factor in dead reckoning is the accuracy of the sensors used to detect driving distance and directions. Although highly accurate and highly expensive sensors were used in submarines and aircraft, it was not cost effective to use them in automobiles. US-based Etak developed a method to achieve correct location detection without expensive sensors. This method was map-matching which, assuming that the vehicle moves on roads, compares the vehicle's trajectory detected via dead reckoning with a map and corrects the errors, thereby minimizing cumulative errors produced by the sensors and detecting the correct location. Figure 1 shows a schematic for illustrative purposes.

The blue line represents the dead reckoning-based trajectory. Slight deviations in driving distance and direction result in a gradually accumulating error from the true location on the road indicated with the green line. When the vehicle makes a turn at an intersection, map-matching accesses road map data to search for the location of the intersection and corrects the vehicle's current location to the intersection location.

The red line represents the corrected trajectory based on map-matching. The trajectory is corrected to be on the road, which reassures the driver. Sumitomo Electric pondered whether or not to adopt Etak's technology. Differences concerning road density and road configuration between Japan and the United States and other substantial discrepancies that would affect the logic, as well as prospects for future development, made the company develop the required technology in-house.

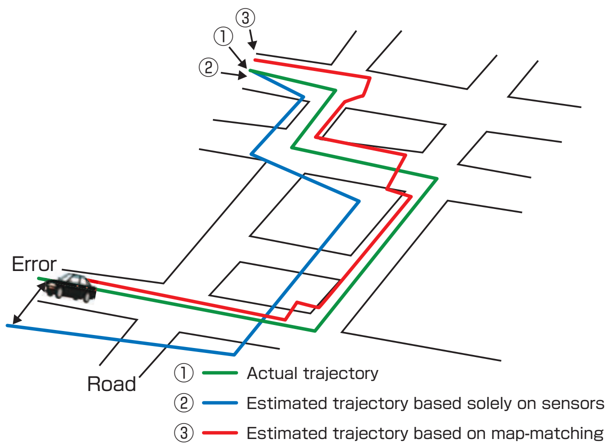

Fig. 1 Principle of map-matching
(Courtesy: Sumitomo Electric Industries, Ltd.)

2) Sensor hardware and software concept

Sensors are required to detect the travel distance and rotation angles. Requirements for use in automobiles include low cost of the order of hundredths to thousandths of the cost of sensors for submarines or aircraft, relatively good accuracy, no need for servicing, and ruggedness during the service life of the vehicle which is some ten years.

Travel distance and rotation angles are determined based on the average number of revolutions of both wheels and the differences between them. Since Sumitomo Electric manufactured anti-lock braking systems (ABS), we were familiar with ABS wheel speed sensors and asked automakers to allow us to use them as travel distance and rotation angle sensors. Since rotation angle sensors are incapable of indicating the absolute direction, a magnetic field sensor was also incorporated. Wheels slip, so the number of revolutions of a wheel differs from the actual travel distance. Magnetic field sensors are subject to substantial errors depending on the location, such as a point close to a DC-driven electric train. Thus, it became critically important to develop software to correct these errors by map-matching. To test the software, we drove actual vehicles on various courses and conducted simulations using data acquired from the actual driving. Nonetheless, it had turned out through the test driving and simulation that the accuracy of the rotation angles determined from the difference between both wheels was inadequate. Eventually, we developed an optical fiber gyro[6], which will be discussed later. Other components were selected for automotive use from those used widely in automobiles and that were sufficiently reliable and durable under vibration and high and low temperature conditions. To display a map and the optimal route, we first used a six-inch CRT (some vehicles already had them installed). Maps were recorded on a CD-ROM. In 1989, a NAVS incorporating these systems was adopted for the Cedric and Cima (Fig. 2). Today, the CRT and CD-ROM have been replaced by an LCD unit and either a DVD or a hard disk.

Fig. 2 Vehicle navigation system
(Courtesy: Nissan Motor Co., Ltd.)

NAVS produced around 1990 used six-inch CRTs. The NAVS was positioned where audio and air-conditioner controls had been previously installed. Audio and air-conditioner control functions were included in NAVS features.

3) Commercialization concept

We used ABS sensors as wheel speed sensors for our NAVS. Accordingly, our NAVS could be installed only in vehicles that had an ABS system, while at that time, few consumer vehicles were equipped with ABS. Requirements concerning the magnetic field sensor included: erasing magnetic effects of the iron body by the automaker during production; recording sensor constants by revolving and checking the magnetic orientation; and subsequent automatic correction by wheel speed sensor readings and map-matching.

In location detection by map-matching, it is basically necessary to set a starting point. In addition, the actual road may differ from the map and the vehicle location may be lost during driving. On such an occasion, it becomes necessary to re-input the starting point where the vehicle location is identifiable. Since this would have to be carried out by the user, it was necessary to reduce the frequency of such occasions and to make operation simple.

To meet these requirements, it was necessary to make displayed information easy to read and the starting point setting operation simple. Consequently, in addition to the software for vehicle location detection and route navigation guidance, the software for information display and NAVS operations gained monumental importance.

This NAVS system required a digital road map for map-matching in addition to a map for display. Since such a map did not exist, we decided to develop one ourselves (explained later).

In addition, the NAVS display played an important role as a vehicle information display unit. Software was developed to display vehicle information. Target prices were roughly ¥50,000, ¥100,000 and ¥200,000. Using a large color display, no significant cost reduction could be expected. Basically, the NAVS was an expensive commodity. Although aftermarket units were available, their inexpensive yet small displays were subject to poor readability. They were not suitable to be marketed as original equipment manufacture (OEM) systems that needed to ensure safety, and therefore we excluded them from the options.

(2) Developing orientation detection gyros

1) Developing an optical fiber gyro[6]

Regarding sensors used to measure vehicle rotation angles, the accuracy of determining the difference in the number of revolutions between both wheels is not precise enough. Because of this problem, early NAVS frequently got lost, with map-matching capacity limits being exceeded. We believed it was necessary to improve the accuracy of the rotation angle sensors. Thus, we explored the ways to reduce production costs of the optical fiber gyro (sample priced at millions of yen) that had been developed at Sumitomo Electric at that time for robots used to work in adverse conditions, and to remodel this gyro into one for the NAVS. Fortunately, we ourselves could produce most parts required for the optical fiber gyro. We mass-produced each part at a low cost and lowered precision to reduce the cost to a level acceptable for NAVS applications. A double digit cost reduction was somehow achieved, and it became possible to install it in the vehicle. The introduction of the optical fiber gyro contributed to improved performance to a level where the NAVS would get lost only once or so per 200 km driving.

2) Vibration gyro[7]

The GPS became available for NAVS in 1990. Since then, optical fiber gyro-level accuracy has not been highly required for rotation angle sensors. Instead, lower-cost sensors have been in demand. As vibration gyros designed to prevent camera shake emerged on the market, we explored the possibility of using them for NAVS. Vibration gyros designed for cameras were aimed at detecting hand motion, with no consideration given to offset drifts occurring over an extended period of time. We drew up specifications and requested sensor suppliers to develop a vibration gyro for NAVS. It has turned out that Murata Manufacturing Co., Ltd. was able to produce an almost satisfactory gyro sensor, enabling us to replace the optical fiber gyro with a vibration gyro. We did not solely rely on the performance improvement of the vibration gyro itself, but also provided the gyro-handling software with additional functions such as offset drift estimation during driving and estimation of the drift amount by gyro temperature measurement. Because of these software capabilities, the vibration gyro we employed was smaller and less expensive than the optical fiber gyro, yet was five times greater in zero offset.

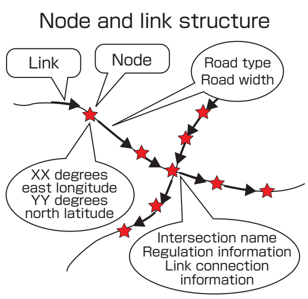

Fig. 3 Road configuration data
(Courtesy: Sumitomo Electric Industries, Ltd.)

Fig. 4 Plotting example of actual roads
(Courtesy: Sumitomo Electric Industries, Ltd.)

3.2 Development of route calculation and guidance technologies

Since accurate detection of the current location was achieved, there were demands for capabilities to determine the optimal route up to the destination and to guide the vehicle to turn right or left during driving. Route computation algorithms were developed largely in academic laboratories. Prerequisites to route computation were often huge memory and map data storage allowing for fast readout. In contrast, with NAVS it was necessary to quickly compute 500 km routes between Tokyo and Osaka using the base speed of CD-ROM and lowest cost memory. We made route computation fast, spending only 30 seconds, instead of the 30 minutes required by the conventional method.

3.3 Development of digital road maps

(1) Providing a map database

Map-matching requires digitized map data, in the configuration of which an intersection and section between intersections are referred to as a node and a link, respectively. Map-matching data contains road connection relations, one-way traffic regulations and other information. Thus, it is far more elaborate data than map data structured solely for display purposes.

In Fig. 3, nodes are intersections and curves on roads and come with information such as coordinates, intersection names and connected links. Links are vector data in which nodes are connected by straight lines, containing information such as road attributes and widths.

Figure 4 shows an example of actual roads. Roads connecting to an expressway constitute many links that imitate actual curves. Figure 5 shows a displayed map, which contains water systems, building shapes, place names, facility names and other information for readability.

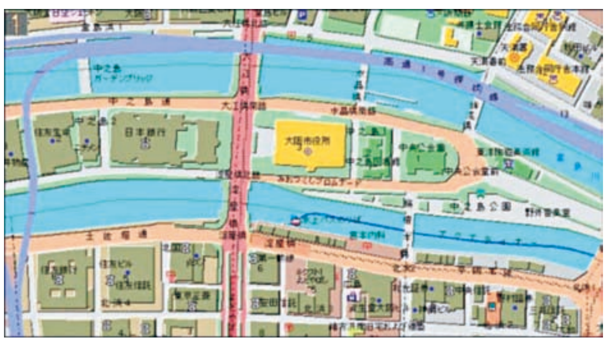

Fig. 5 Example of map data display
(Courtesy: Sumitomo Electric Industries, Ltd.)

At first, each NAVS supplier independently began data development. Sumitomo Electric developed data for the three metropolitan regions based on detailed map data such as 1:2500 urban planning maps issued by power companies, gas companies and municipalities. This process required permissions from municipalities. Our development staff branched out and visited municipal governments to obtain permission.

(2) Japan Digital Road Map Association[8]
Independently-developed map data was sufficient to meet early metropolitan application requirements. As there were growing trends toward wider use of the NAVS, however, each supplier became aware that map data should not be developed separately by private businesses, spending a large number of man-hours and large expense. Accordingly, we worked on interested sectors. Our efforts led to establishing the Japan Digital Road Map Association to develop digital road maps, with the then Ministry of Construction taking the initiative. Key issues in founding the association were specifications (standardization) and members (user attraction). One major achievement was that automakers decided to cooperate in the domain of surveys and editing for the industry's sake while leaving the domain of designing how information is displayed for the competition. Participants from the then Ministry of Construction were the Road Bureau and the Geospatial Information Authority of Japan. Although shared use of map data implied loss of differentiation, private businesses took part in the association, providing funds and member fees and sending engineers, in anticipation of cost reductions.

Meanwhile, functional requirements for map data have changed with the advance of the NAVS. Simply displaying the current location, the first generation was required to ensure network accuracy. The second generation, which displayed a route to the destination, met the needs for information on regulations, such as one-way traffic, right/left turns and presence/absence of a median strip. The third generation, displaying traffic information, was required to ensure consistency with traffic jam data management units. Since then, the Digital Road Map Association has provided data to sustain the NAVS in Japan. Route navigation was achieved by combining the original map data with the no-right/left turn and other traffic regulation data administered by the police.

3.4 Receiving traffic information

Japan makes optimal use of traffic networks constructed on its narrow land. Road traffic management in Japan is the most advanced in the world. Traffic jam conditions have been monitored by numerous vehicle sensors[9], image sensors and intersection-monitoring cameras installed on roads. Traffic jam information was provided to NAVS via multiple media: FM broadcasting administered by the then Ministry of Posts and Telecommunications; radio wave beacons[10] on expressways administered by the then Ministry of Construction; and optical vehicle detectors[11] (optical beacons) on general roads under the control of the National Police Agency. The Vehicle Information and Communications System[12] (VICS) Center was founded through the efforts of interested parties. Information collected at the VICS Center was sent to NAVS via each media center. This scheme enabled NAVS to obtain information on nationwide traffic jam conditions. Thanks to the efforts of involved parties from the business sector, we were able to overcome the challenge of integrating the different mediums and were able to develop a uniform format for shared data sent via radio waves.

Again, data processing software was important for receiving data from the beacon. It was necessary under any display conditions for the NAVS to instantly display simple graphic data unique to a specific location, sent from a beacon, as with handling an interrupt. Receiving beacon data at times of high CPU or memory load, as when changing to a different display scale or route re-searching, resulted in heavy demands on internal processing.

In providing traffic information, it was necessary to ensure correspondence among expressions of map data containing traffic jam information, data at the VICS Center, and data on onboard NAVS units. A solution was developed thanks to the efforts of interested parties.

In Fig. 6, green and red arrows on the map represent uncrowded and crowded roads, respectively. In 1973, CACS envisioned coordination between onboard equipment and infrastructure. A coordinated system was finally achieved in 1996 when NAVS had become popular and VICS was established.

3.5 Development of other core components

The NAVS was required to perform map-matching and show computation results of a route up to the destination and route navigation in real time over the map on the display. This resulted in a need for large memory, software size and computational power previously unseen with conventional onboard equipment. Semiconductor memory in the initial phase of development was far below the required level of capacity to store display and map-matching maps within the

Fig. 6 Map displayed with traffic jam information

practical scope of applications. We selected CD-ROMs even though the media was seldom used in vehicles at that time. In employing CD-ROMs, we introduced CD drive suppliers to an oil damper developed by Tokai Rubber Industries, an affiliate of Sumitomo Electric, so that CD drives could withstand vibrations in the vehicle.

Furthermore, ROM was selected as program memory to store programs up to 1 Mbyte. For map operation memory, we selected DRAM, although it was also rarely used for automotive purposes. We employed these devices with automotive environmental testing and reliability considerations in mind.

The United States started refining the GSP for military purposes in around 1988, and the system has been permitted to be used by civilians with intentionally reduced accuracy. GPS made it possible to determine the current location without the aforementioned sensors in vehicles, only requiring the provision of a receiver. In around 1990, GPS NAVS emerged on the market, which were mostly off-the-shelf NAVS because they were easy to install. At first, since there were not a sufficient number of satellites in the sky required for positioning, GPS NAVS became useless in tunnels and in the shade of buildings where no satellite was in view. In around 1995, however, GPS NAVS became almost practically useful. When the effect of accuracy degradation was removed in 2001, they easily reached the practical level.

3.6 Promoting sales to customers

Sumitomo Electric developed digital road maps of Osaka and the surrounding areas, tested the NAVS and began appealing to automakers six months after we independently started developing the NAVS in 1983. Our project was highly regarded by Nissan. Mass production of map-matching NAVS incorporating wheel speed sensors, a magnetic field sensor and a 1:2500 map commenced in 1989 with a planned monthly output of 1000 units for the Cima and Cedric, although the unit needed to improve in positioning accuracy. In 1991, we offered optical fiber gyro-equipped NAVS for the Cedric and Cima. Subsequently, however, Nissan founded Xanavi Informatics Corporation jointly with Hitachi as an attempt to develop NAVS in-house. Thereafter, although our systems were selected by customers excluding Toyota, a substantial amount of man-hours required to meet customized requirements resulted in huge deficits, and this became problematic in terms of business operations.

Meanwhile, audio manufacturers and other suppliers began offering aftermarket NAVS, which gradually became predominant. Although we speculated that OEM NAVS would go mainstream as a driving assist system in the future, we entered into a competition in the aftermarket against the will of some of our employees because we considered that gaining a reputation in the aftermarket was indispensable to our survival in the business. While many GPS NAVS displayed current locations away from roads or even on a lake according to GPS-detected coordinates, our positioning accuracy and quick route computation, achieved with OEM onboard NAVS, were well-received.

4 NAVS business: development and withdrawal

4.1 Development cost burden and business profitability

As we worked on NAVS hardware development, along with improvements in location detection, view for the map, route computation and route guidance, and paying costs of nationwide map development and updating, it was impossible to continue the NAVS business without successful prospects for business profitability. To recover these costs, required NAVS sales were at least 20,000 units per month.

Vehicles equipped with an OEM NAVS at that time numbered some thousands per month at each automaker, although the number was very large at Toyota, to which Sumitomo Electric was not shipping. We received orders totaling less than 10,000 units per month even during busy periods. At that time, we thought that the NAVS market would explode and our sales volume would soon reach a profitable level. Contrary to our expectations the market growth halted after the burst of the bubble economy, and our business was constantly underperforming. One cause of the failure of our NAVS business model was that we could not develop a scheme in which automakers would pay the heavy costs of map data and software development.

Consequently, to somehow improve profitability, we collaborated with our competitors in map database construction and even in NAVS development.

4.2 Onboard NAVS software development problems

After entering the aftermarket, we still worked with multiple automakers on developing OEM NAVS. With them it was necessary to enable audio and air conditioner controls to be displayed on the same screen. Different vehicle families came with different instrument panel designs and the number of switches installable on the instrument panel would also change. The presence or absence of one switch necessitated a substantial software revision, as in the case where use of a different cell phone model entails a substantially changed feel of operation. After 1995, in addition to adapting the NAVS to different vehicle families, we implemented novel major software features such as VICS reception and access to the Internet. In order to launch new features such as VICS support and Internet connections ahead of competitors in such a period it was important to standardize the software so that the functions could be simply expanded.

To ensure that the above-mentioned adaptation and launch of new features met multiple automakers' requests, we needed highly capable development staff, which resulted in software development costs dragging the business down.

Nonetheless, Sumitomo Electric was then developing our original NAVS operating system aiming to boost the performance of NAVS. Our aftermarket NAVS launched in 1995 was highly regarded due to its fast operation. On the other hand, specialized operating system and application software necessitated operating system upgrading for adaptation to different vehicle families of individual automakers and for implementing novel functions. To provide access to the Internet, it was necessary to develop a new original browser. These difficulties in providing new features incurred huge software development costs and man-hours. As a result, by necessity, we requested automakers to give up implementing some features.

In the meantime, the NAVS released in 1997 underwent specification changes, which in part caused software development man-hours to increase from the initial estimate of some 200 man-months to 1000 man-months at the time of completion, resulting in a substantial cost increase. Moreover, the software had so many bugs, which were detected after the release, which raised maintenance costs and substantially increased the deficit. This was one major factor in our pulling out of the NAVS market.

Meanwhile, “concentration on core competence” became a keyword in the business sector. Sumitomo Electric decided to withdraw from the NAVS business because it had run up huge deficits and had no prospects of improvement.

5 Summary

The NAVS has been successfully developed not simply by NAVS software development, but through synergetic effects of developing substantial infrastructure and related technologies, such as a map database, traffic information, communication modes and various hardware units. Today’s widespread use of NAVS has been achieved through cooperation among persons concerned at the then Ministry of Construction, the then Ministry of Posts and Telecommunications and the National Police Agency; Toyota, Honda, Nissan and other automakers; many NAVS suppliers including Denso, Mitsubishi Electric, Alpine and Pioneer; Panasonic, Hitachi and other infrastructure developers; and component suppliers involved in developing small vibration gyros, GPS, display units and other components.

Figure 7 shows technologies and components employed in NAVS as well as related infrastructure in chronological order. Accordingly, the NAVS is complete, consisting of a number of technologies, combinations of components and software that ensures efficient use of them.

Map data evolved from proprietary data possessed by individual companies to shared data. Sensors technology saw the emergence of vibration gyros. When GPS was developed, it became simple to detect the current location with high accuracy. As display devices, the price of LCDs fell. Trends in the area of functional enhancement were improved performance of CPUs, increased memory size, and advances from CD-ROM to DVD or HDD.

Another factor contributing to the widespread use of NAVS was the simultaneously developed infrastructure. The Japanese Intelligent Transport System (ITS) emerged as NAVS became popular and has now become essential to automobiles. Subsequently, the development of the electronic toll collection system followed.

The NAVS plays the role of an information center in a vehicle, displaying images of onboard cameras and various other pieces of information. Integration between the NAVS and driving control is advancing, as exemplified by automatic deceleration before the intersection at which the vehicle is to make a turn. Meanwhile, portable navigation devices (PNDs) are becoming popular abroad at a remarkable pace. NAVS are expected to be more ubiquitous in the future, becoming polarized into high-end OEM NAVS and affordable PNDs.

Acknowledgments

The development of NAVS for practical use has been achieved through the efforts and contributions made by many involved parties from the industrial, governmental, and academic sectors. We hereby recognize their achievements and express our gratitude to them. We need to mention that former Sumitomo Electric executives Nobuo Yumoto

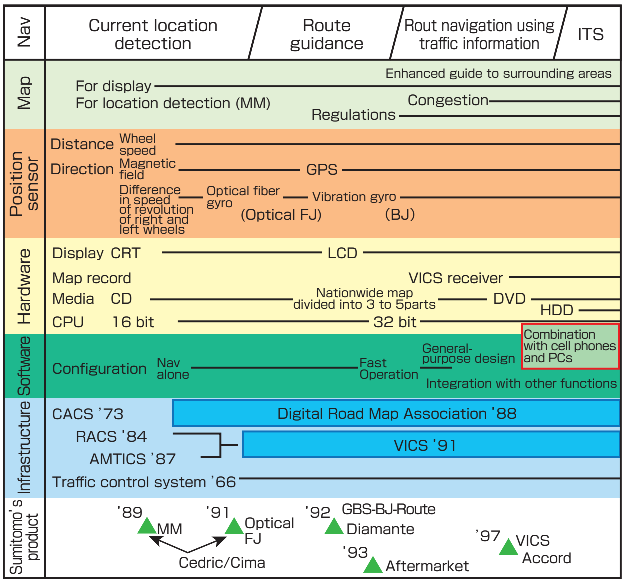

Fig. 7 Correlations in development of car navigation system

and Kunihiko Mito contributed to solving many problems involved in developing NAVS. We would like to express our thanks to Mr. Mito for his support in preparing this paper. We have promoted the development, commercialization, onboard installation, and other plans for the NAVS. However, the project turned out to be unsuccessful as a business, and we had no choice but to withdraw from the NAVS business. In conclusion, as the individuals responsible for the project, we would like to express our heartfelt regret for having caused a great deal of inconvenience to many involved parties over the period of the project.

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Authors

Hirosaka Ikeda

Graduated in 1964 from the Department of Applied Chemistry, Faculty of Engineering, Kyushu University. Joined Sumitomo Electric in 1964. Oversaw automotive wire harness development, vehicle electronics and NAVS. Took up the post of Managing Director in 1999, post of President at AutoNetworks Technologies, Ltd. in 1995 and moved in 2008 to the present post of Special-Appointment Professor at the Innovation Training Program Center for R&D and Business Leaders of Kyushu University. In this paper, Ikeda was in charge of the background to NAVS development, promotion, relationships with core technologies and management.

Yoshinobu Kobayashi

Graduated in 1967 from the Division of Electrical Engineering, School of Engineering, Osaka University. Joined Sumitomo Electric in 1967. Worked on wiring harness electronics and NAVS development. Took the post of Manager, Automotive Electrical & Electronics Div. in 1999. Moved to the post of Executive Chief Engineer, AutoNetworks Technologies, Ltd. in 2000, then present post of temporary employee. In this paper, Kobayashi was in charge of hardware development. He strived to improve the profitability of the NAVS business and implement restructuring.

Kazuo Hirano

Graduated in 1974 from the Department of Applied Mathematics and Physics, Faculty of Engineering, Kyoto University. Joined Sumitomo Electric in 1974. Began to work on wiring harness electronics and NAVS development in 1981. Took the post of Manager, Automotive Electrical & Electronics Div. in 1996. Moved to the post of Deputy Director, Automotive Technologies Laboratories. and then to the present post of Manager, Strategic Planning Div., Automotive Business Unit. In this paper, Hirano was principally in charge of onboard NAVS software development and VICS construction.

Discussions with Reviewers

1 General

Comment (Akira Kageyama, Research and Innovation Promotion Headquarters, AIST)

The content of the paper is suitable for *Synthesiology*, as it concisely describes extensive elemental technologies used in car navigation systems (NAVS). The paper makes it clear that a wide range of technologies is required to launch a product to the market. At the same time, it describes what technologies are employed or dismissed in order to achieve a goal, and how a specific technology is combined with those in other fields. The paper is of great value in providing an example of corporate research and development management.

Furthermore, despite its limited number of pages, the paper mentions the establishment of the Japan Digital Road Map Association, collaboration with other corporations, and cooperation with government agencies as important elements of research and development management. This makes the paper a representative one on *Synthesiology*.

2 General perspective on combining individual elemental technologies

Comment (Akira Kageyama)

The paper refers to: (A) location detection, (B) route calculation and (C) route guidance as key elemental technologies and, beginning with map-matching, introduces. the reader to candidate technologies usable for the completion of (A), several technologies suited to the completion of (B) and a few technologies needed to complete (C). I think the paper can include an illustration or a list of elemental technologies used to complete NAVS as a practical technology, in order to help readers unfamiliar with the subject field understand the topic. Such an illustration or list would facilitate reader understanding of the need of a lot of technologies in producing NAVS.

Comment (Motoyuki Akamatsu, Human Technology Research Institute, AIST)

If a figure is provided showing how course changes were made when selecting technologies regarding each individual major technological element, such as map-matching, location identification, digital map and route calculation, depending on new factors of the time (GPS, CPU and storage devices), readers would immediately understand that the development scenario underwent dynamic changes to keep up with technology trends.

Answer (Hirosaka Ikeda)

We inserted Fig. 7 in “5. Summary” to show relationships among elemental technologies.

3 Importance of software technology development for unified control of diverse hardware technologies

Comment (Akira Kageyama)

The paper states that not only sensor technology, but also software technology is important. I think it is better to place more emphasis on the importance of OS and other software research and development. Software appears to play a critical role in combining sensor technology and digital maps, location correction and processing of data received from radio-wave or optical beacons.

Answer (Hirosaka Ikeda)

A NAVS is an onboard device in which software technology plays an important part, as you point out. Its software size is far larger than those of other onboard devices. The paragraph on vibration gyros in subchapter 3.1 of the paper now has an additional description about software improvement needed for the use of vibration gyros, since they are poorer than optical fiber gyros in performance of the hardware itself, specifically in drift amount. Regarding beacon data reception, the paper describes the need for complex internal processes due to intensive loads, such as switching to an interruption screen after receiving beacon data.

4 Technological development process

Question (Akira Kageyama)

The paper states that a huge increase in software development cost necessitated the withdrawal of Sumitomo Electric Industries, Ltd. from NAVS business. Sumitomo Electric’s withdrawal is very regrettable, since the company led the industry in the early days of NAVS. Nonetheless, could you please, from an engineering or industrializing perspective, summarize key technological or management points that enabled NAVS and ETC to later develop into high growth industries?

Answer (Hirosaka Ikeda)

(1) Key points that led to high industrial growth

1) One key technological point is that the NAVS is, as with television, a commodity that is used repeatedly. Once a customer tries it, he or she cannot go without it. Take the example of television in the early days; people argued, from an educational point of view, that they had no need for television in their homes, as it would lead to home environment degradation. Today, multiple television sets are found in every home.

The NAVS was in a similar situation in its early days. Most staff at automakers’ electronics divisions said that automobiles did not need navigation systems. One said: “What are you doing, Mr. Ikeda, at this busy time? You should stop fiddling with NAVS development.” He later took the post of NAVS development manager and said: “Mr. Ikeda, I was wrong.” At that time, market surveys showed that few people wanted a NAVS in their cars. On the other hand, interestingly, one automaker executive did not trust so-called marketing approaches. He said: “Mr. Ikeda, it’s meaningless to ask customers whether they want a product that is not yet on the market. They have no idea.” Professional taxi and company drivers said that they needed no NAVS, that looking at a map would be sufficient. The NAVS has now become a necessity for them. In this sense, the NAVS is a driving assistance system. Derivative words from NAVS are now used in other fields, proving the wide acceptance of NAVS.

2) Few automotive parts cost more than ¥10,000, and even fewer exceed ¥100,000. However, the NAVS has proven that expensive onboard equipment can be viable. Moreover, the NAVS involves extensive supporting industries. For instance, there is a market even for onboard LCD alone.

3) NAVS software was the largest embedded automotive software. Since its quality and reliability requirements were far higher than those in other industries, including the PC industry, NAVS software improved noticeably. As with hardware, software quality requirements are high in the automotive industry. Users would immediately notice defects. General IT companies would not be able to take part in genuine brand NAVS production. Company distinction was created in that business sector, according to quality. The sector was characterized in that zero bug tolerance was a fundamental requirement. But this was a trap that Sumitomo Electric fell into when conducting its development management.

(2) Software breakthrough

When you build software, you need to think about both functional differentiation through pursuit of your originality, as well as ease of expandability provided by commonality. In my view, Sumitomo Electric was preeminent above all others in NAVS performance. However, in the years following 1995, it became necessary to add major features such as compatibility with VICS and support for the Internet. We should have been aiming for commonality at that time. Nonetheless, Sumitomo Electric took the course of developing its proprietary OS in order to achieve functional differentiation and fast operation. As a result, the company had no choice but to provide major additional features by itself. We revised the paper to include this information.

5 Information on Etak’s NAVS

Question (Motoyuki Akamatsu)

Etak, the company that released the world’s first map-matching technology, launched a NAVS in 1985, while the paper states that Mr. Yumoto became interested in map-matching technology in 1983. Did he learn about the technology because there were some papers on map-matching published before Etak commercialized it?

Answer (Hirosaka Ikeda)

When Yumoto, then working for Sumitomo Electric, visited

America on a business trip, he got information from Dr. Robert French, a NAVS trailblazer, and tried Etak's prototype NAVS. Incidentally, the map used for that NAVS was a simple one.

6 International comparison of NAVS proliferation

Question (Motoyuki Akamatsu)

Concurrently with Gyrocator, developed by Honda Motor Co., Ltd., Electro Multi Vision by Toyota Motor Corporation and Sumitomo Electric's system, US-based Etak developed and launched their NAVS. Eventually, NAVS came into widespread use in Japan. Why the difference, do you think?

Also, I would like to hear your view on why the Japanese industrial sector was highly motivated and why the Japanese government showed a positive attitude toward NAVS.

Answer (Hirosaka Ikeda)

(1) Differences in NAVS proliferation

In the United States, cities have streets and avenues neatly arranged in a grid pattern. Access points to inter-city roads are numbered and easy to follow, reducing the need for NAVS. For route guidance in America, itemized information is more often used than maps, further reducing the need for map-based NAVS.

In Europe, by contrast, city states of long history have winding roadways that are extremely difficult to follow. In such places, the NAVS is readily accepted, as in Japan.

Japanese people are generally early adopters. In addition, the country had advanced technologies for NAVS, including gyro sensors, displays, CD-ROM drives, semiconductors and traffic information communication systems.

(2) In the motivated industrial sectors, NAVS system and map development was promoted by automotive, car electronics, audio, electric and map manufacturers. Parts suppliers worked on gyro sensors, GPS, semiconductors including microprocessors, CD/DVD/HD drives and displays. Moreover, many emerging IT companies entered the market as a new field for them and provided embedded NAVS software.

(3) The government, I think, was interested in NAVS as a new industrial sector involving infrastructure.

7 Distinction from review papers

Comment (Akira Kageyama)

Readers of this paper may have the impression that it is a review of the technological development of NAVS, or a research and development history. Therefore, it is recommended that it be stated why a specific technology was selected from among a set of candidate technologies for research and development, and in what aspects the selected technology was superior to the other candidate technologies, by providing semiquantitative data or something similar.

Answer (Hirosaka Ikeda)

Regarding the optical fiber gyro, we inserted a sentence: "The introduction of the optical fiber gyro contributed to improved performance to a level where the NAVS would get lost only once or so per 200 km driving." For the vibration gyro, the following has been added: "We did not solely rely on the performance improvement of the vibration gyro itself, ... Because of these software capabilities, the vibration gyro we employed was smaller and less expensive than the optical fiber gyro, yet was five times greater in zero offset."

8 On *Synthesiology* paper

Question (Motoyuki Akamatsu)

Your present paper is on NAVS development and commercialization. Could you please mention specific information that you have provided for the first time in the *Synthesiology* paper and may not have included in other papers for conventional journals?

Answer (Hirosaka Ikeda)

In the paper we could write:

(1) Process behind the NAVS development at Sumitomo Electric
(2) Process behind the optical fiber gyro development conducted to improve positioning accuracy
(3) Process behind the creation of an unprecedented digital map database
(4) Relationships with automakers
(5) Development of aftermarket NAVS
(6) Business profitability and development cost issues
(7) Software defect issues

What we could not write was considerable, including:

(1) Inter-government agency coordination issues
(2) Difficulty associated with parts procurement
(3) Marketing to approach customers
(4) Responses to various relevant events (From a business promotion perspective, it was not necessarily wise to actively participate in events.)
(5) Objections from members of Sumitomo Electric
(6) Relationships with competitor manufacturers
(7) Alliances

New material development by the integration of cast technology and powder metallurgy technology

— A high-performance hard material which used intermetallic compound for binder phase —

Keizo Kobayashi *, **Kimihiro Ozaki, Akihiro Matsumoto and Hiroyuki Nakayama**

[Translation from *Synthesiology*, Vol.3, No.4, p.301-308 (2010)]

Hard materials made of ceramics combined with metals are used for dies and cutting tools that support high precision processing technology in Japan. Hard materials, however, need a large amount of rare metals that are scarce as resources as component and hence developing new materials with less dependence on rare metals has been expected. We developed a new hard material with Fe-Al intermetallic compound as a binder. This material was synthesized by a process combining casting and powder metallurgy and exhibited high hardness and high strength simultaneously. This paper introduces an approach to "*Type2 Basic Research*" in order to apply the developed material to industrial use, and a method of efficient research and development through the collaboration of researchers of different specialized fields.

Keywords : Cemented carbide, FeAl, mechanical alloying, pulsed current sintering, die, cutting tool

1 Background of research

Cemented carbide, which is widely used in molds and cutting tools, is a composite material with high strength and hardness. It is fabricated by sintering hard tungsten carbide with cobalt. It is an essential material for precision machining technologies, which are used by many Japanese advanced industries, for example, automobile industry and information appliance industry. Cemented carbides have a long history. Japanese exports of carbide tools are increasing annually, with an increase of over 350 billion yen reported in 2007 (statistics according to the Japan Cemented Carbide Tool Manufacturers' Association). However, with increasing global industrialization, concern over the long-term stable supply of tungsten and cobalt is growing. Particularly, the rare metal cobalt has been subject to radical price fluctuation. Furthermore, the development of a new metallic binder phase is highly desirable from the environmental perspective. For these reasons, AIST started directing efforts toward the development of a new composite material of a metal and ceramic with high strength and hardness.

An ideal metal for use in these composites is iron, which is an abundant resource with a stable price. However, the use of iron presents significant challenges owing to its high reactivity with carbides (e.g., tungsten carbide) and its propensity to rust. Therefore, cemented carbides with iron as the binder phase have not been previously used practically. However, there is a demand for cemented carbide for use in high-temperature applications in the machining industry. For example, the use of cemented carbide in cutting tools will facilitate both high-speed cutting and unlubricated cutting, and its use in molds will facilitate forming processes in middle to high temperature ranges. It is anticipated that such applications will reduce energy consumption during the forming process, contributing to the goal of achieving a low carbon society. It is essential to provide heat resistance to the binder phase of the cemented carbide for these applications.

In this paper, we describe the development at AIST of a new cemented carbide using an iron aluminide intermetallic compound[1] as the binder phase. We present an evaluation of its mechanical characteristics and a property evaluation required for its industrial use and applicability to peripheral technologies. This research was carried out by a group consisting of several researchers with different specialties.

2 Objectives and goals of the research

The effective use of intermetallic compounds to improve the heat resistance of hard composites is well documented, with reports of comprehensive studies by universities, private companies, and national institutes in the project of the Ministry of Economics, Trade and Industry since 1990. As a consequence, intermetallic iron-based materials were considered. Intermetallic compounds comprise an ordered phase of different metal elements, and are known to exhibit properties somewhere between those of ceramics and metals. Particularly, the aluminum-based intermetallic compound called "aluminide" shows reverse temperature dependency of the material strength, and offered promise as a metal-based material for use in the middle-high temperature range. Through collaboration with private companies, AIST has previously studied the synthesis of aluminide

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intermetallic compounds using casting technology, synthesizing intermetallic compounds including titanium aluminides (TiAl, Ti_3Al, etc.) and iron aluminides (FeAl, Fe_3Al, etc.). Because the aluminide intermetallic compounds are composed of elements with large specific gravities and large melting point differences, the degree of segregation proved too large for the traditional melting method or casting technique. Therefore, a new process technology called levitation melting and casting was developed. However, through simply casting the molten metal, the microstructure of the iron aluminide intermetallic compound became coarse, and sufficient strength could not be obtained. At the same time, AIST was developing the semi-solid forming technology as a casting technique for shaping magnesium alloy with fine microstructure. This technique involves the application of high pressure to partially molten alloy, and produces both the near net shaping by thixotropic properties and the high strength given by fine microstructure. Moreover, we considered powder metallurgy technology as a synthetic method for the production of aluminide intermetallic compounds, and investigated the synthesis of aluminide intermetallic compounds with fine microstructure using the mechanical alloying method[2]-[4].

With the technologies for the material design and manufacturing processes almost completed for the WC-Co cemented carbides, the research was conducted mainly for the development of finer hard particles. The demand for cemented carbides has increased with the increased speed and precision of machining technology, and as a consequence, there have been further demands for cost reduction. Particularly, an alternative to, or means of reducing the amount of, cobalt (which can be subject to extreme price fluctuation) and tungsten (which suffers from variable resource availability) was sought.

Therefore, we started the development of a new process technology for a new hard material using an aluminide intermetallic compound as the binder phase by fusing technologies, i.e. the various known technologies for intermetallic compound synthesis and technologies based on our knowledge of cemented carbides. By using Fe and Al instead of Co as the binder phase of cemented carbides, we developed a process in which only Al was liquefied in the sintering process, followed by the synthesis of a FeAl intermetallic compound. By using this technology, we created a new hard material with heat resistance, as a result of compositing the hard particles of tungsten carbide, titanium carbide, or titanium boride using this iron aluminide intermetallic compound as the binder phase. To enhance the feasibility of this new material replacing conventional WC-Co cemented carbides, we set the goal for the newly developed composite material to exhibit 900 Hv or more in hardness and to surpass 2 GPa in three-point bending strength.

3 Research scenarios to realize our goals

In this technological development, the mechanical strength of the composite material was determined by the close contact force of hard particles and iron-aluminide intermetallic compounds, which filled the gaps between these particles. The method of fabricating a porous preform of hard particles and then pressure-injecting the molten iron aluminide intermetallic compound, and the method of mixing and stirring the hard particle powder into the molten iron aluminide intermetallic compound were investigated, but sufficient strength could not be obtained owing to low adherence between hard particles and intermetallic compound in this method. Therefore, we studied a new process in which hard particles of high melting point are forcibly mixed by mechanical stirring[4] with the iron and aluminum powders that are the components of the intermetallic compound as the binder phase. We believe that the hard particles were coated with metallic powders, since the metallic powder is highly ductile.

Following this, we fabricated a WC-FeAl alloy (WC-8.6 mass% Fe-1.4 mass% Al) using a method that was similar to a manufacturing process for conventional cemented carbides. WC powder, Fe powder and Al powder were wet-mixed by attrition ball milling at desired constituent and sintered at 1440 ºC in a vacuum. The conventional cemented carbide (WC-Co) was fabricated by liquid-phase sintering in which the binder phase was melted; high-temperature sintering was also necessary in the case of WC-FeAl to increase the adherence of the binder phase and hard particles. The obtained sintered compact showed excellent resistance to oxidation, even when heated to 800 ºC in air, and when the compact was treated by hot isostatic pressing (HIP), the bending strength was maximum 1.8 GPa. However, strength variations were observed in the obtained compacts, and it proved difficult to manufacture a stable compact; the composition and volume of the binder phase could not be accurately controlled as Al with a low melting point evaporated during vacuum sintering. In addition, the evaporated Al may adhere to the graphite electrode and other devices in the vacuum sintering furnace, and the fabrication of this WC-FeAl hard material using the conventional process was considered impractical.

The evaporation of Al during sintering may be caused by the insufficient reaction of Fe and Al during wet mixing. To address this, we then applied the mechanical alloying (MA) method, which is a dry mixing method that uses large mixing forces to synthesize the alloy, to produce WC-FeAl. It has already been established that the MA method for aluminide intermetallic compounds can be achieved using an amorphous alloy powder and that a significant time is needed for the alloying of Fe- and Al to progress. When the long-term MA was conducted at high energy, the adherence of the hard particles and the binder phase strengthened, and sintering at low temperature could be expected. The long-term MA was carried out using planetary ball milling, and the obtained mixture was then sintered at 1200 ºC[5] to produce a material with a fine microstructure. However, the bending strength of the compact was only 0.8 GPa. No improvement in strength was observed with increased quantities of binder phase, with the binder phase flattening out progressively[6]. Thus, even by expanding the conventional cemented carbide manufacturing process, we were unable to achieve a WC-FeAl hard material with the desired properties. Consequently, we entered the so-called “valley of death”; however, we were unable to continue the joint research with the companies, and the road to realization seemed to be closed.

Therefore, we abandoned the conventional WC-Co cemented carbide manufacturing process, and shifted to the application of pulsed current sintering technology, which our research group developed as a method for bulk compacting amorphous powders, for sintering our WC-FeAl hard material. Pulsed current sintering is a technology for fabricating a sintered compact with a fine microstructure in a short time and at low temperature by electrically heating and pressing simultaneously. It is a suitable technique for solid phase sintering. Since the pressing separated the liquid, this method was considered unsuitable for the sintering of cemented carbides that feature a liquid phase. However, a desired intermetallic compound was synthesized through the reaction of Fe and Al before the Fe was melted in the sintering process, when the homogeneous mixture of WC and Fe produced in MA was sintered after adding Al powder. Using this reaction, the Al melted at low temperature (660 ºC) in the pulsed current sintering, and the sintering progressed as the FeAl intermetallic compound was formed. Since the Al content in the WC-FeAl hard material was small, the Al liquid only infiltrated the gaps in the powder and did not separate by the pressing. By using the pulsed current sintering, the interior of the sintered compact could be heated evenly by Joule heating between the powders. In general powder metallurgy processes, organic lubricants are used during pressing and forming, but in this new process, the molten Al was thought to play the role of the lubricant. The pressing and forming in the presence of molten Al employed the same mechanism as the semi-solid forming technology, and we succeeded in obtaining the densified compact by utilizing our knowledge from the semi-solid forming technology of the Mg alloy. The reaction between Fe and Al was slightly heat generating, and a slight volume change occurred during the synthesis of the intermetallic compound to produce pores, but WC-FeAl compact could be sufficiently densified by subsequent heating. The developed process is shown in Fig. 1. The obtained WC-FeAl compact almost met our desired bending strength and hardness prerequisites[7][8]. We were finally able to make an object as a new hard material. In the new fabrication process, which combined the dry powder synthesis process and the pulsed current sintering process[9]-[11], we were able to fabricate a prototype of a new hard material that might replace some of the conventional cemented carbides, though still at laboratory level. However, the Al addition was considered to be a taboo in the conventional cemented carbide and was not accepted readily in the associated industry. Additionally, as it required special sintering equipment, the research and development for the practical use could not progress, despite the fundamental technology being in place.

Analyzing the process of fundamental technology development, the improvement of material properties were enhanced not only by our basic knowledge of cemented carbide but also the various approaches of numerous researchers with diverse knowledge of powder metallurgy, pressure sintering, and the technology to observe the microscopic region of controlled boundaries, who became interested in this hard material, for which AIST owned the composition patent. As a result, we were freed from the bind of the conventional cemented carbide manufacturing process, and were able to develop a new process based on novel ideas. Since the researchers engaged in solving this problem each had their own individual approaches, unique technologies that reflected the individuality of the researchers were

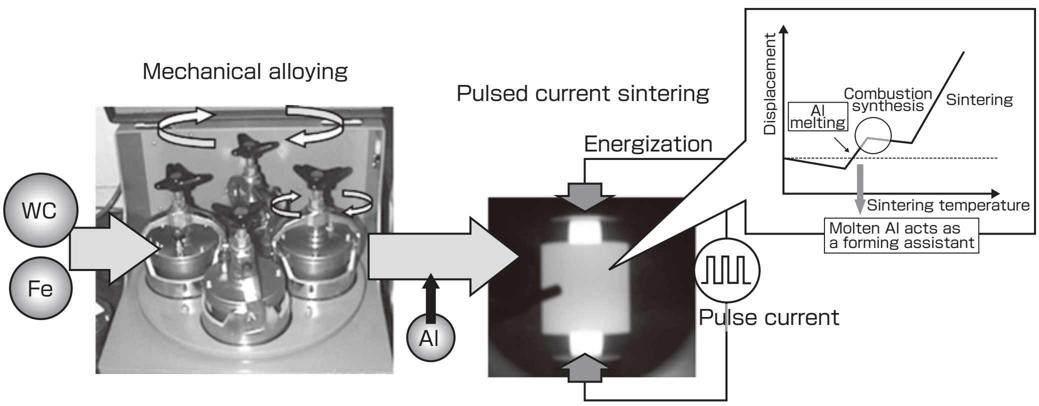

Fig. 1 Preparation process of newly developed WC-FeAl hard material

developed in the stage from *Type 2 Basic Research* to product realization.

4 From *Type 2 Basic Research* to product realization

For the newly developed WC-FeAl hard material to be adopted widely as a practical material, it was important to find companies that would manufacture this material on an industrial scale. Even if the new material could be manufactured with the new process and showed excellent properties, no company that wished to engage seriously in this material could be found. However, as we have been presenting our information about the new hard material at academic conferences (the Japan Society of Powder and Powder Metallurgy) and elsewhere, industries were interested from the initial stages of the research. Therefore, to promote the practical use of the new material, we decided to collect experimental data deemed necessary by the companies by suggesting the products for which the material could be used. We positioned this stage as the *Type 2 Basic Research* that was difficult to carry out at universities or companies owing to the high-risks involved. We utilized the AIST "High-Tech Manufacturing" project and carefully scanned the keywords for using the WC-FeAl as a mold. The technological topics for realization were: (1) fabrication of large sintered compact for a practical mold, (2) a finishing process by conventional machining technology to determine the machining cost of the WC-FeAl hard material, and (3) resistance to thermal shock by heating-cooling, assuming the use of the mold in high temperature. Since some of the problems could not be addressed in our laboratory setting, we sought cooperation from universities and companies.

In the fabrication of the large sintered body, as the pressure forming using the molten Al was used in the developed process, we found that molten Al functioned as the forming additive and the densification of the sintered body could be achieved with relative ease. By using high-voltage sintering equipment of greater capacity and applied pressure than that available at AIST, a large sintered compact with the same function as that achieved in the basic research was fabricated. The obtained large sintered compact is shown in Fig. 2. Its size (φ140 mm) would allow its use as a small mold. In the finish of the cemented carbide product, electro arc machining and wire cutting were used. These processes took advantage of the high conductivity of cemented carbide. Since the developed WC-FeAl sintered compact had high conductivity similar to conventional cemented carbides, wire cutting and electro arc machining could be used under the same machining conditions. In the wire cutting process of conventional cemented carbide, the machined surface reacted slightly and became discolored. However, there was little reaction in the case of WC-FeAl hard material owing to the good acid resistance properties of the FeAl phase. The WC-FeAl hard material sintered at AIST was processed into a mold (for small gear manufacture) at a machining company, and the appearance of the finish was the same as that obtained with a cemented carbide mold, as shown in Fig. 3. The time required for machining was about the same as the conventional cemented carbide. It was also confirmed that the new hard material could be processed at similar cost to the conventional cemented carbide. If this mold could be used for high-temperature forging, the processed material could be heated and then formed at high speed with a small forming load at high temperature, and the energy required for the process could be reduced. In general high-temperature forging, the molds are sometimes water-cooled. Therefore, we performed an experiment in which cemented carbide was heated to 900 ºC in air and then quenched in water. The appearance of the rapidly cooled samples is shown in Fig. 4. In the conventional cemented carbide, oxidation progressed rapidly, an oxide layer formed on the surface of the sample heated in the air producing a blue color, and cracks were produced due to heat stress when cooled rapidly. On the other hand, while the WC-FeAl hard material became slightly reddish-brown due to the thin oxide layer on the surface, it did not produce cracks. The developed WC-FeAl hard material did not readily oxidize when heated in the air, produced few cracks when water-

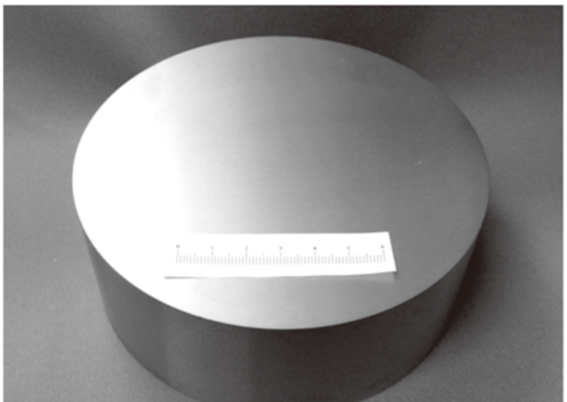

Fig. 2 Photograph of a large-size WC-FeAl sintered body

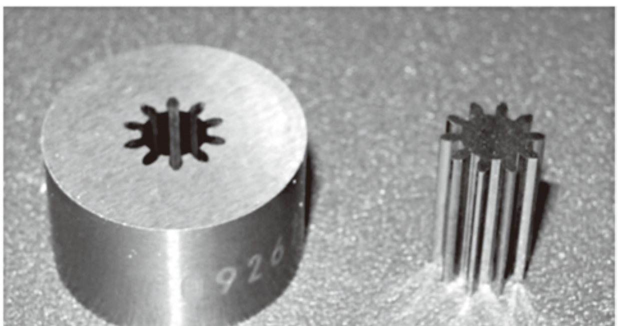

Fig. 3 Photograph of the mold made using WC-FeAl

cooled, and could be envisioned for use as mold material for high temperature.

Moreover, the WC-FeAl hard material showed machining precision at processing speeds equivalent to the conventional cemented carbide in the grinding process using abrasive stone. A prototype of the complexly shaped blade of a ball end mill was fabricated. This blade tip was able to perform equally to conventional cemented carbide, as shown in Fig. 5. However, in this ball end mill, the new material was used only at the tip that was joined to the high-speed steel rod by brazing. This was because a long sintered compact cannot currently be fabricated with the newly developed process, this being a subject for future study.

The result of this *Type 2 Basic Research* greatly reduced the timescale to the adoption for practical use. Several companies expressed desire to actually use this material. All of these companies wished to manufacture the material on their own. They wanted to introduce the new process technology, and then investigate the practical uses and business applications by combining the new technology with their own technology. Therefore, we set the cutting tools and molds as the outlet, and performed the examination to practical use through the research involving the material manufacturers and the machining companies.

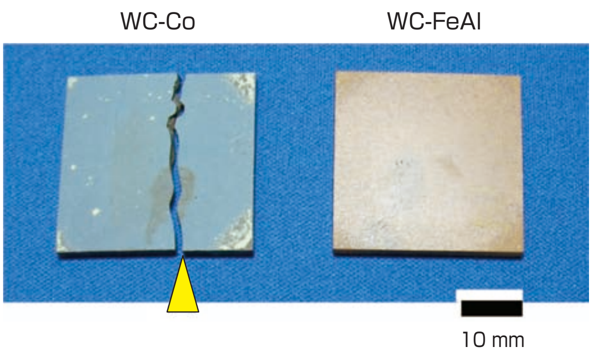

Fig. 4 Photograph of WC-based hard materials quenched in water from 900 °C in the air
WC-Co (conventional material) is cracked, but the WC-FeAl is not cracked.

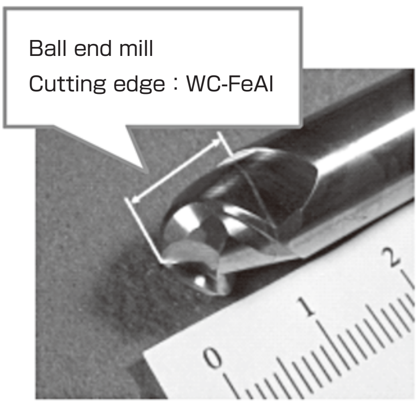

Fig. 5 Prototype ball end mill made using WC-FeAl

5 Discussions

The developed WC-FeAl hard material is a new composite material using FeAl intermetallic compound as the binder phase, and has the potential to resolve the problems associated with conventional WC-Co cemented carbide. For example, Co, which is the binder phase of the conventional cemented carbide, has a Vickers' hardness of 130 Hv, and is softer than tungsten carbide. Therefore, when the surface of the cemented carbide is polished, some unevenness occurs between the binder phase and hard particles. On the other hand, the FeAl intermetallic compound has a Vickers' hardness of 320 Hv, and the unevenness caused by the hardness difference between the binder phase and hard particles should be reduced. To examine this, the WC-FeAl hard material in which the volume ratio of the binder phase had been adjusted, and the conventional WC-Co cemented carbide were both polished with diamond abrasives, and the surfaces were coated with diamond-like carbon (DLC) by sputtering. Although there were some differences due to the observed area in the coarseness of the polished sample surfaces, values were Ra = 4.3 nm for the WC-FeAl, and Ra = 5.3 nm for the WC-Co; the polished surface was smoother in WC-FeAl because the binder phase was hard. When the adherences of the DLC film formed on each hard substrate were measured by a scratch test, the WC-FeAl required approximately 25 % higher load for separation. It was confirmed that in the boundary between the DLC film and the cemented carbide substrate, the even DLC film adhered

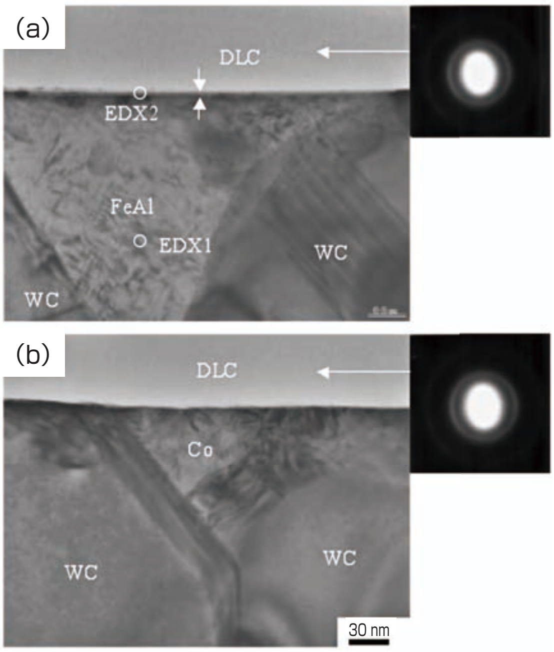

Fig. 6 Microstructure observation of the interface portion of DLC film and the WC-based hard material
(a) Interface of DLC and WC-FeAl.
(b) Interface of DLC and WC-Co.
Aluminum oxide is formed at EDX2 area of (a).

on top of the hard particles and binder phase, as shown in Fig. 6. When the boundary of the WC-FeAl and the DLC film was observed microscopically, a thin layer was observed in the boundary. When this layer was analyzed carefully, it was found that an aluminum oxide film was formed, and this was thought to increase the oxidation resistance at high temperature. This thin layer formed at approximately room temperature and was found to improve adherence to the DLC film. When the DLC film is formed on the surface of WC-FeAl hard material, it is expected to increase the mold release characteristics of the formed material. In fact, the WC-FeAl die whose the surface was coated with DLC reduced the force that was necessary for blanking of Mg foil and Cu foil.

In the WC-FeAl hard material fabricated by the developed process, the crystal growth of the WC particle, which was known to be a problem in the conventional cemented carbide, was hardly observed during sintering. In addition, there was no formation of a composite carbide phase such as the W_3Fe_3C that is known to be a brittle phase. In the early stage of the development, we did consider these results closely as these were considered to be the result of low-temperature sintering. However, some researchers are beginning to investigate the effect of Al from an academic aspect, and it is necessary to examine further the interaction between the carbides and the FeAl intermetallic compounds. As we devoted most of our efforts towards practical use, there is a lack of academic considerations, and we intend to investigate this further through joint researches with universities.

By using a hard material FeAl as the binder phase, it was possible to reduce the amount of tungsten carbide whilst attaining the same hardness, and it is thought that the use of the WC-FeAl hard material will result in tungsten-saving technology. However, there is only a little reduction effect of the tungsten by this method. A hard particle other than tungsten carbide must be composited to further reduce tungsten usage. Considering the recent rise in tungsten prices, immediate measures are highly valuable. Therefore, by using the fabrication process of WC-FeAl, we investigated the compositing of titanium hard particles and FeAl. We attempted the development of a hard material in which titanium boride particles with high heat conductivity were bound with Fe-Al intermetallic compound[12][13]. The obtained TiB_2-20 mass% (Fe-Al) sintered compact had more than 95 % of the theoretical density. While its hardness changed according to the Fe:Al ratio, it was over 1500 Hv. Since the sintering property of the TiB_2 particle was good when the Fe content of the binder phase was high, the Fe-Al intermetallic compound with high Fe content was used. In addition, the TiC-30 mass% TiB_2-30 mass% (Fe-Al) hard material, in which the titanium carbide and titanium boride particles were used as hard particles and Fe-Al intermetallic compound was used for the binder phase, showed heat conductivity of 30 W/mK, and had intermediate value between the conventional cemented carbide and cermet (TiC-Ni alloy). As various additional uses are found for cemented carbide in which the WC is bound by the FeAl intermetallic compound, we anticipate that new uses will be found for the TiB_2-(Fe-Al) or TiC-TiB_2-(Fe-Al) hard materials. In fact, the TiB_2-(Fe-Al) hard material is lighter than cemented carbide, and new applications to wear-proof parts can be considered by further evaluating the abrasion resistance.

6 Summary

Herein, we describe details concerning the development of a WC-FeAl hard material with excellent resistance in AIST, and explain the R&D from the basic research to *Type 2 Basic Research* undertaken in our research group. Figure 7 shows the schematic diagram of the course of the development. It can be seen that the current WC-FeAl was created as a result of the fusion of various elemental technologies over

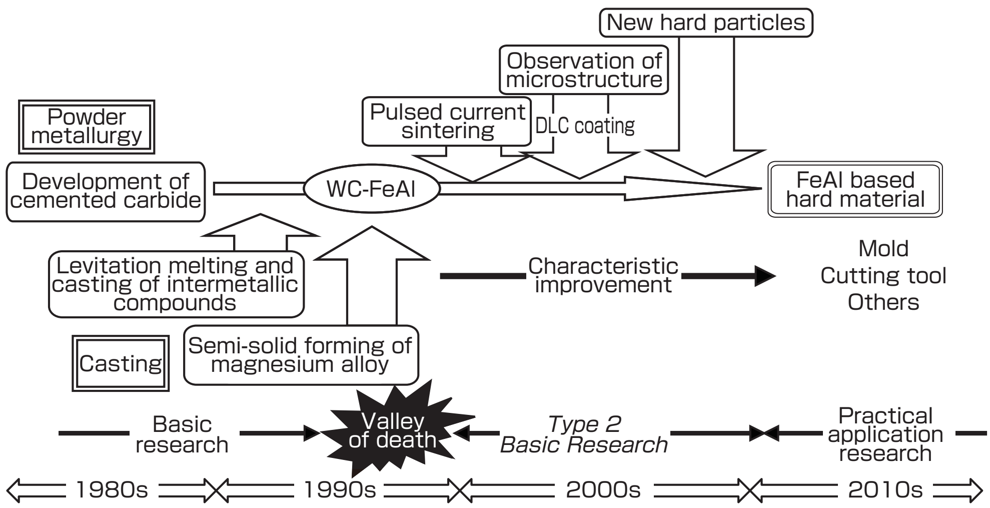

Fig. 7 Development process of WC-FeAl hard material

time. When the development of the hard material began, we aimed to replace some uses for cemented carbide, and it was clear that the outlet would be molds and cutting tools. Fortunately, the researcher who discovered this material had prior experience with cemented carbide in industry, and we were able to set the goal toward its realization relatively easily. It was difficult to achieve the targeted values using the conventional cemented carbide manufacturing process of the original hard material developed by AIST, but we were able to solve the issues steadily through the addition of new perspectives of researchers who were not directly involved in cemented carbides. However, the achievement of the target values did not lead to immediate practical utilization. By consistently transmitting the information at academic conferences for hard materials and by obtaining advice from the companies, we were able to find issues that brought us closer to realization. As a project for realizing this developed material, we obtained support from the Regional Consortium and the Strategic Core Industry Advancement Support Project (Support Industry) of the Ministry of Economy, Trade and Industry. Currently we are undertaking work towards realization through a collaboration of industry-academia-government, in addition to working towards establishment as a business. In the future, while the price increase of cobalt and its effects on the human body continue to cause concern for cemented carbides, further use can be expected due to the advancement of this development. The systems for supplying large and complex shaped members are being established, and we shall be able to provide samples to companies that are interested in this material. Our researchers are uniting to provide useful industrial material in the form of new hard materials featuring our WC-FeAl material.

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Authors

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Obtained master's degree at the Department of Metallurgy, Graduate School of Engineering, Osaka University in March 1986. Initially joined Kobe Steel, Ltd. and then moved to the Nagoya National Industrial Research Institute, Agency of Industrial Science and Technology in 1989. Research interests include levitation melting and casting for titanium alloys, semi-solid forming technology for magnesium alloys, and non-equilibrium powder synthesis technology by mechanical alloying. Doctorate (Engineering) obtained at Osaka University in July 1997. Leader of Phase Engineering for the Processing Group, Institute of Structural and Engineering Materials, AIST in April 2001. Leader of Phase Engineering for the Advanced Material Group, Material Research Institute for Sustainable Development from April 2004. In this disclosure, developed the WC-FeAl hard material using experience with cemented carbides, obtained the patent, proposed the overall plan, and managed the research.

Kimihiro Ozaki
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Doctorate (Engineering) obtained at the Department of Metallurgy and Department of Iron and Steelmaking, Graduate School of Engineering, Nagoya University in March 1992. Joined the Nagoya National Industrial Research Institute, Agency of Industrial Science and Technology in April 1992. Engaged in the development of high melting point structural intermetallic compounds, the synthesis of titanium amorphous and quasi-crystal alloys and energy use, and the development of environmentally-friendly cemented carbides. Leader of Structural Control Research Group, Material Research Institute for Sustainable Development in 2007. In this disclosure, expanded the results into use as cutting tools, and developed the DLC coating technology based on microscopic structure observation.

Hiroyuki Nakayama
Doctorate (Engineering) obtained at the Department of Functional Materials Engineering, Graduate School of Engineering, Toyohashi University of Technology in March 2004, followed by post-doctoral positions at the University of Washington and the Nagoya Institute of Technology. Joined AIST in April 2008. In this disclosure, developed the compositing and mixing technologies of various hard particles and Fe-Al intermetallic compounds to expand the research to tungsten-saving technology.

Discussions with Reviewers

1 Market scale of cemented carbides and effect of cobalt free product

Comment (Norimitsu Murayama, Advanced Manufacturing Research Institute, AIST)

To have the readers from different fields appreciate the economic significance of cemented carbide and the effect of achieving cobalt free hard material as the background of your research, I think you should numerically present the market scale of cemented carbide, share of Japan, and economic effect of achieving cobalt free.

Answer (Keizo Kobayashi)

According to the statistics of the Japan Cemented Carbide Tool Manufacturers Association, the domestic production of cemented carbide in FY 2007 grew to over 350 billion yen. Although it decreased after the Lehman Shock, a market scale of over 200 billion yen is maintained, and has since increased. In the international share of cemented carbide, Japan's Mitsubishi Material Corporation and Sumitomo Electric Industries, Ltd. follow Sandvik AB, Kennametal Inc., and Iscar Ltd. However, we were unable to obtain accurate figures for the share of the Japanese companies. For the effect of cobalt free, along with the cost reduction of the raw material (in raw material price, compared as reagents, the iron and aluminum powders are less than 1/4 of cobalt powder), certain aspects, such as the environmental concerns (carcinogenic issues) and the application to new high-temperature uses, are difficult to express numerically. As you indicated, we added and modified the text to include the figures where we could. The forging mold that we are developing from *Type 2 Basic Research* to application research has a market potential of about 15 billion yen (source from the Materials Process Technology Center).

2 Originality of the research

Comment (Norimitsu Murayama)

The number one originality of this research is to use Fe and Al instead of Co as the binder phase of cemented carbide. Al is used as the binder phase in the liquid state during sintering, and FeAl is synthesized to work around the disadvantages of Fe and Al. I think the paper will mature by explaining this point in chapters 2 or 3. The second originality is that you found that if both Fe and Al are in liquid form, Al evaporates rapidly and the synthesis does not go well, but when only Al become liquid, it functions as the binding agent and the synthesis of FeAl will progress. This is an example where the result did not go as in the scenario designed by thought experiment, but a way opened by patiently conducting experiments.

I think you can communicate the dynamism of the material research to the readers if you divide "3 Research scenario to realize the goal" into the scenario design by thought experiment and the changes in scenario after the actual experiments.

Answer (Keizo Kobayashi)

As you have understood, the greatest characteristic of this research was the use of Fe and Al instead of Co. Al is melted during sintering, and the target intermetallic compound is synthesized by subsequent heating. I added this point to chapter 2. In addition, I think by what process the WC-FeAl alloy is fabricated is very important in this research. While we were developing the material by following the concepts of the conventional cemented carbide, we were unable to synthesize stable materials, even though we could clarify the properties of the materials. Afterwards, we did some alternative thinking, and various secondary effects were found by reviewing the process. As a result, we were able to advance the research greatly. I added the points that you indicated and modified the "3 Research scenario to realize the goal". However, since I was unable to discern the extent to which the thought experiment would cover, I intentionally did not use the word "thought experiment".

3 Time needed for material development

Comment (Norimitsu Murayama)

Material development takes a long time. This is one characteristic of material development. Why don't you add a time axis to the development of WC-FeAl hard material in Fig. 7, and add some explanation in the text?

Answer (Keizo Kobayashi)

As you indicated, I think the addition of the time axis will be effective in enabling readers understand the progress of the material. However, in practice, the technological developments progressed side by side, and I feel it is difficult to present an exact time axis. Though very rough, I added a time axis in units of decades to Fig. 7 to emphasize that long time was needed for the material development.

4 Selection of elemental technologies for practical utilization

Comment (Hisao Ichijo, Tsukuba Center, Inc.)

This is a description of a series of processes from the need of R&D, the material synthesis, the evaluation of properties, and the development of new hard material through fusion research. The process of selection and integration of the elemental technologies is important in *Type 2 Basic Research*, and I think it will help the understanding if you explain the selection process.

Answer (Keizo Kobayashi)

As you indicated, I added a brief explanation of the selection of the elemental technologies. For the topics for the material and the process of considering its use as the mold material, I got the idea from hearing the comments of the private companies at the academic conferences.

In high-tech manufacturing, we focused on the medium to high-temperature mold as an outlet. Using the WC-FeAl hard material, for which we have been evaluating the basic properties (mechanical properties, oxidation resistance, wear test, etc.), we conducted experiments for creating material of significant size to fabricate a mold that can be used industrially, for the usability of conventional cemented carbide processing to evaluate the machining cost, and for the evaluation of cracks and oxidation by repeated heating and cooling. These items were selected by talking to the companies that showed interest in this material at academic conferences (Japan Society of Powder and Powder Metallurgy). I added and modified the text to clarify the background.

5 Effect of pulsed current sintering

Question (Norimitsu Murayama)

Please tell us the effect of the pulse current sintering. If the process involves forming at low temperature range of 660 ºC and combustive synthesis reaction that is followed by sintering, isn't it possible to fabricate the target hard material by ordinary pressure sintering?

Answer (Keizo Kobayashi)

Using the basic idea in this process (forming by molten aluminum, combustive synthesis reaction, and sintering), I think for small compacts, it can be done by a process in which heating and pressing can be done simultaneously, as in the hot press. However, for large compacts, external heating using a heater as in a hot press causes temperature differences between the area near the heater and the central part of the compact. This causes a time lag in the production of the liquid phase of aluminum and the following combustive synthesis reaction, and it would be difficult to fabricate an even sintered compact. This is a finding that we made during semi-solid forming; in pulsed current sintering, the current goes inside the compact allowing Joule heating between the powders, and this controls the occurrence of temperature difference compared to the external heating method. As a result, I believe we were able to fabricate a sintered compact without cracks, as the Al liquid phase acted evenly as a forming additive in the fabrication of the large WC-FeAl sintered compact.

Clinical research and synthesiology

[Translation from *Synthesiology*, Vol.3, No.4, p.309-314 (2010)]

Among medical researches, the clinical research utilizes results of the basic research for society in the form of therapy. President Higuchi of the National Center of Neurology and Psychiatry (NCNP) and Ono, Editor in Chief of *Synthesiology* discussed the situation of clinical research in Japan. They shared common goals between the clinical research in the medical field and synthesiology.

***Synthesiology* Editorial Board**

Participants: Dr. Teruhiko Higuchi, President, National Center of Neurology and Psychiatry
Dr. Akira Ono, Editor in Chief, *Synthesiology*
Moderator: Dr. Motoyuki Akamatsu, Executive Editor, *Synthesiology*

(Moderator)
To utilize the results of scientific research in society, we believe the research that pursues a methodology for synthesizing and integrating the elemental technologies is important as well as the conventional analytical and pure basic researches. In the field of medicine, there are basic and clinical researches. Can you explain whether these two are essentially different disciplines, and what exactly is clinical research?

Type 2 Basic Research and clinical medicine

(Higuchi)
The essence of medical research is to develop a new therapy to treat the patient, and to seek new therapy by studying the cause of a disease. In medical research, there is the approach where one becomes directly involved in the disease to understand it, and also the approach where the elements and foundations that comprise the human body and the diseases are investigated thoroughly, and then the actual disease in humans is confronted with such knowledge and technology. Basic medicine studies the functions of normal cells and the workings of normal neurons, while clinical research looks at the pathological conditions and the diseased tissues. Basic medicine existed throughout the ages. Physiology developed in the ancient times not because people wanted to know the cause of diseases, but because people were naturally curious about “how the human body is composed” or “why does the heart beat on its own”.

On the other hand, clinical medicine is an application of the understanding of how the physiological functions change into a pathological state, using the knowledge and information obtained in basic medicine. There are studies in which humans and diseases are used as direct subjects, to reveal the differences between a normal individual and a diseased individual. In some cases, large-scale clinical researches are conducted using several hundreds or thousands of human subjects to see whether a drug really works or whether it is a placebo effect (where the natural healing effect is observed due to the psychological effect of taking the drug, even though there is no actual pharmaceutical effect).

(Moderator)
There are clinical researches using disease-model animals, but there are also different kinds of clinical research where a large-scale research is done to determine whether it is applicable for human treatment.

Dr. Ono (left), Dr. Akamatsu (center) and Dr. Higuchi (right)

(Ono)
I think that the discussion about the basic medicine and the clinical research may lead to the analogy of the *Type 1* and *Type 2 Basic Researches*. There are dreams in the pure basic research, and the researchers who attained their dreams may win Nobel Prizes and receive research funds fairly easily. There is a great gap in terms of time and technology, however, for the basic research results to become actual products in industry and to be used in society. I think that some synthetic and integrating approaches are necessary for the basic research results to become valuable to society.

(Higuchi)
If *Type 2 Basic Research* is what is called application research, I think the researches that involve animal models and diseased cells can be positioned as such. The large-scale clinical research where humans are used as subjects is close to *Product Realization Research*. I think there is a shortage of research on how to get the products out to society. For example, considering anticancer drugs, one may induce cancer in an animal and prove that the cancer disappears when a certain drug is administered. However, it will not be a “drug” unless it is proven that it really works in humans and that there are no side effects.

(Moderator)
In the sense that it is a way of studying the therapeutic effect using human subjects, can clinical research be categorized as disease-oriented research? Is it like clarifying the disease mechanism?

(Higuchi)
The approach may be a bit different from mechanism clarification. Both pathological research and therapy research use humans as subjects. For example, to study the pathological condition of the Alzheimer’s disease, in the past, we could only look at the brain tissue of the deceased patient under the microscope. Now, with the advancement of imaging technology, we can look directly at the brain image of the living patient to study the pathological condition of Alzheimer’s disease. While this is a pathological research using human subjects, it is not therapy research. Therapy research falls in the domain of clinical research.

Dr. Teruhiko Higuchi

(Moderator)
Up to the pathological research, the mechanism of a natural phenomenon called the disease is clarified, and that may be close to *Type 1 Basic Research*. When this knowledge is converted to therapy, it turns into *Type 2 Basic Research*.

TMC bridges the pathological study and the therapy

(Ono)
In the field of medicine, does a researcher engage in either the pathological research or the therapeutic one? Or can a researcher engage in all from the pathological to therapeutic researches?

(Higuchi)
Both cases are possible. Let me talk about an example of the study carried out at NCNP. It had been known that muscular dystrophy was a genetically transmitted disease, and a gene called dystrophin was finally discovered by a researcher. After more than ten years we are able to see what kind of abnormal proteins are produced and how they cause the muscles to atrophy. Now the researcher is trying to get to the therapy research.

(Moderator)
Looking at the Japanese clinical research statistics that Dr. Higuchi showed us, I am concerned that the number of Japanese papers published in four journals of basic medicine research with high impact factor (2000~2005) is ranked number four in the world, while Japan ranks eighth in the three clinical medicine research journals, and there are less number of papers.

(Higuchi)
Even if there is an accumulation of excellent papers in basic research, we are not getting the application in clinical practice. We are becoming aware that it is not right that we are unable to produce results that are actually useful to people. On that point, I think we share a common concern with AIST.

NCNP is composed of a hospital and two research institutes. In the past, the institutes were mainly involved in basic research, and there was hardly any contact with the hospital that engages in daily clinical practice. However, when we were organized as an independent administrative agency, the consciousness that we should engage in the researches covering “from basic research through application research to clinical research” has risen in the past five to six years. As a move, the Translational Medical Center (TMC) started in 2009. TMC places the importance on linking the research and clinical practice, and to support clinical trials and researches to promote translational medicine for the clinical research in psychiatry, neurology, myology, and developmental disorder.

Why Japan has fallen behind in large-scale clinical researches

(Moderator)
As in the case of muscular dystrophy you mentioned earlier, there are several basic researches that may offer ideas for therapies. But still there are not a lot of applications to clinical practice. Including large-scale clinical research, why has Japan fallen so far behind in clinical research?

(Higuchi)
A researcher is evaluated for his work of "publishing high-quality, original researches in high-quality journals". A large-scale clinical research can only be conducted by a team of perhaps 40 people, and it involves extremely careful design and preparations, as well as recruiting many patients. This is extremely unproductive for a researcher. It may take five to six years to complete a single clinical research. Moreover, even if a wonderful result is obtained, there is only one first author. For the other 39 people, considering the efficiency of their energy spent, it is much more efficient to design a trial alone, conduct research in a few months using animals, yield results, and become the first author to publish in *Nature* or *Science*. While it is understandable for the people to think this way, it is one of the reasons that this field has not advanced. In the United States, research funds and human resources are allotted, and there could be multiple authors who are evaluated for participating in the research. I think there are differences, and Japan has definitely fallen behind.

(Moderator)
The background for falling behind in large-scale clinical research seems to be similar to our situation, i.e. the motivation to launch *Synthesiology*. What do you think, Editor in Chief?

(Ono)
Dr. Higuchi mentioned that one of the reasons for being left behind in clinical research is the problem of "paper productivity in research". At AIST, when we tried to focus on *Type 2 Basic Research* as a bridge spanning between *Type 1 Basic Research* and *Product Realization Research*, we were requested, "Please evaluate us as researchers. There is no journal in this field. What should we do?" That is why *Synthesiology* was created. Although it is still in its dawn, we have been thinking hard how the papers published in this journal are different from the papers of what we called basic science, and what makes them original. Also, we disclose the name of the reviewers. With ordinary academic journals, the tendency is to keep the reviewers anonymous, and the names of the authors are apt to be hidden to the reviewers to maintain the fairness. We did the opposite. We disclosed what points were given credit and what points were not. We ensured transparency. In fact, this worked positively in terms of fairness. Because the names of reviewers are disclosed, they cannot ask careless questions or make biased comments.

(Moderator)
Are there other reasons that prevent the advancement of clinical research?

(Higuchi)
As a nation, the government has not placed importance on clinical research, has not provided funds, or trained human resources.

The pharmaceutical companies engage in large-scale clinical research, but they are limited to the cases where there are many patients who may eventually use the product. Serious diseases with fewer patients require support of the government. The recently started "clinical trials sponsored by investigators" are conducted mainly by physicians through public research funds, without the direct involvement of the pharmaceutical companies.

In terms of training human resources, the education system is still insufficient. To conduct clinical research, we need specialists in biostatistics and epidemiological statistics, but there are hardly any courses at the universities. Therefore, most people study abroad and return to work at pharmaceutical companies. To conduct large-scale clinical research, one must design it on how many cases are needed to obtain the required statistical significance. However, there are only about five university courses for clinical epidemiology. Even though the researchers may be motivated, there was no environment for clinical research, and its importance was not shared by the government, university, or research institutes. As a result, Japan was left far behind.

(Ono)
Sometimes I hear the phrase "drug lag".

Dr. Akira Ono

(Higuchi)
It means that the drugs that can be used in other countries cannot be used in Japan, because the system of clinical trial is insufficient here.

(Moderator)
The basic researches for medicine were very active in the United States, and then they started talking about translational research. Was that because the genetic researches came into focus?

(Higuchi)
There was a great breakthrough where suddenly there were potentials for application of genetic analysis. If the genetic studies did not go far, the bioscience researches might not have been stimulated as much today.

(Moderator)
The reductionist explanation now reaches the level that allows synthesis. That is the world of elementary particles in physics, and it's genes in medicine. Because we were able to uncover the element of the mechanism, now people can offer new ideas.

(Higuchi)
How can things be quickly shifted over to clinical research? This is certainly a background for the emergence of translational research.

However, many psychiatric disorders and chronic lifestyle-related diseases such as diabetes are the results of combination of genetics and environment, and they are very complex systems.

What is necessary to promote clinical research

(Moderator)
Although the importance of shifting from basic research to clinical research is understood by society, in Japan, there is no training for the translation part, and there are also issues with the researchers' awareness. Is there hesitation for a researcher or a physician engaging in basic research to shift to clinical research?

Dr. Motoyuki Akamatsu

(Higuchi)
I'm sure there are interests. However, if one wishes to do so, one must put the main job aside. Particularly, since it is difficult for a researcher to venture out to the site of clinical practice, a team is necessary. Since it is difficult for a researcher to become directly involved in clinical trials, it is necessary to create a team of researchers and clinical practitioners who share a common thinking, mediated by someone in the role of a clinical research coordinator (CRC).

(Ono)
Will that be the role for the national institutes or the independent administrative agencies?

(Higuchi)
I think so. The National Center that harbors large-scale research institutes and a hospital fits well in the role. It is necessary to form a team where the members play their respective roles and work together toward a common goal. The National Center has stated that we are eager to take that role. I think it is difficult for a university to do that since they act by laboratory units.

I don't think there are many organizations that are capable of conducting everything from start to goal, from creating a product in their labs and then verifying the product in clinical situations.

(Ono)
A pharmaceutical company with very large capital can design everything from research to clinical practice, and then conduct large-scale clinical research, can't it?

(Higuchi)
The research institutes of the Japanese pharmaceutical companies are very competent, and have excellent ideas to create new compounds. Yet these compounds cannot be verified in Japan. They are taken to foreign countries, and then are re-imported to Japan as drugs.

(Moderator)
From the standpoint of pharmaceutical companies, are there barriers in conducting clinical trials in Japan?

(Higuchi)
I guess the Japanese clinical trial system is both time-consuming and expensive. For example, when a new drug is taken to the United States, the first step will be completed in half a year, while it takes two years in Japan. In that case, it is better that the first step be completed in the States and the drug be re-imported. In terms of market, Japan has a population of 120 million or so, China has 1.3 billion,

and India has 1.1 billion. That is why people are giving up development in Japan and going overseas. The hollowing out of clinical trial is an issue.

Another point is that the capacity of the medical institution is very small. For example, if one wants to do a clinical trial with 100 cases, about 30 institutions must be contacted in Japan. In the United States or Europe, 10 to 15 cases can be done at one institution.

(Moderator)
Is that a matter of the size of the hospital?

(Higuchi)
Rather than the size, it is a matter of how much effort the medical institution is willing to spend on clinical trials. Now, the CRCs are distributed widely, and they can do all the paperwork while the physicians can concentrate on the evaluation. Before, the physicians had to do the paperwork themselves in addition to their clinical duties. They had to spend lots of time on it, and were limited in the extent they could cooperate.

In 2008, the Science Council of Japan issued a statement called the "Issues of Clinical Trials in Japan and Future Measures". They indicated the insufficiency of the clinical trial system in Japan as well as the extremely low incentive for the physicians to become involved. Making the situation worse, since the trials conducted overseas are done for the first time ever, they are published in relatively high-quality English-language journals, while the drug lag in Japan forces the researchers to do third-hand trials for which the result can only be published in minor journals. However recently, Japan is participating from the beginning in global trials, and at least the representative researcher is listed as one of the authors in the English-language journals.

Incentive and support system for the researchers are necessary to promote clinical research

(Moderator)
Is writing papers the incentive for doing clinical research for the physicians at the universities and research institutions?

(Higuchi)
It's papers and research funds. However, there are restrictions with research funds and it is very inconvenient.

(Ono)
There seems to be major problems, but how do you think they should be solved?

Do you think the priority is to succeed with the Translation Research Center of the NCNP?

(Higuchi)
That is the priority. And then, we should provide motivation to the people involved in clinical research. A lot of energy is needed to carry out clinical research. To raise motivation, it is necessary to provide various incentives and to build a support system including coordinators. The TMC was created under the concept of transferring the results of the research institute to clinical practice, but the reverse is also necessary. This means that if a physician has an idea or wishes to do certain clinical research, we must be able to provide support, including helping with the design.

(Ono)
What do you think are the originality and interest of the translational research itself?

(Higuchi)
For the muscular dystrophy research I mentioned before, the first clinical application will be done at our hospital. The hospital is very cooperative because it is an original effort of the Center. The researchers are highly motivated because the research does not just end with discovery and they can be involved in the actual clinical application. However, when this study goes well, I wonder how many places will cooperate if we want to do research using several hundred cases throughout Japan. This will depend on the results of the clinical research sponsored by investigators.

(Ono)
So, in this clinical research sponsored by investigators, things can be taken from small-scale to medium-scale. Do you turn it over to the pharmaceutical company after that?

(Higuchi)
Yes, exactly.

Research accepted and supported by society

(Moderator)
Since clinical research is a process where something is verified in society, I think the awareness that "it must be supported by the entire society" is necessary. If one behaves according to the values of the researcher alone, no one will help any large-scale trial. Don't you think a shift in awareness of society is also necessary?

(Ono)
Also the attitude toward risks is important. The Japanese robot research is at quite an excellent level, but the last frontier is safety. The robot manufacturers become hesitant about product realization, because they think, with any accidents, "How much liability must we take?" or "Is it entirely the manufacturer's fault?" I think it is similar for clinical trials. Is the risk taken entirely by the provider, or does the receiver or society agree to share the risk?

That part is still insufficient, and that's why the robots aren't being sold widely. Robotics is left behind in the clinical trial.

(Higuchi)
Oh, I see.

(Ono)
Therefore, we decided to create safety standards for robots, although it may not be at the level of standards of ISO or JIS. We want to consider safety as much as possible from a public standpoint, and show that such and such safety standards have been cleared. We called this "pilot certification". We make a social agreement for the safety, and then ask the customers to try it out.

(Moderator)
In Critical Path Research and Education Integrated Leading (CREIL) Center of Tsukuba University, we seek help from the network of general practitioners in Ibaraki Prefecture when they conduct translational research. The private-practice doctors can enjoy the opportunity to have hands-on experience with state-of-art medical technology by helping out the clinical research.

For robots, we can say, "There may be risks, but please evaluate them." Then, the people can enjoy the opportunity to work with the state-of-art technology, and perhaps things will turn around well.

(Ono)
It's one of the ways for people to contribute to society. I feel we need such attitudes in medicine and amongst our disciplines, too.

(Moderator)
Those were the general users and doctors, but I think the patients have a different mindset.

(Higuchi)
Comparing the patients in Japan and the rest of the world, there are differences because of the differences in systems. First, the insurance system is different. Japan has the universal insurance coverage, and anyone can receive medical treatment. In the United States, although President Obama is trying to change it, each individual must pay expensive insurance fees. Since the clinical trial is free, people flock to participate.

I think the essence is the spirit of volunteerism. In the United States and Europe, I feel there is strong enthusiasm for volunteering, where people want to do good for others and contribute to society. In Japan, the willingness to participate in a clinical trial is low.

(Moderator)
I feel that there is a tendency for the Japanese to seek benefits but not want to take the risks.

(Ono)
Certainly, I think there are many cases where people cannot judge the balance between the risks and benefits. The universal insurance coverage is an excellent Japanese system, and we attained a society with the highest longevity in the world. Many people feel that we've been successful so far, so we can continue this way, but actually it won't be a smooth ride from here on.

(Higuchi)
I think this also leads to the subject of organ transplant and ODA. We must carry our share of the burden.

(Ono)
I think Japan has attained a safe and secure society quickly. That was very good and a happy thing, but because we attained an ideal society, we cannot take the next step. We cannot muster the energy to go on. Perhaps we are at such a stage. I think the good things about Japan should be left as it is, but some things must eventually change.

(Moderator)
When we are suddenly aware that the earth environment itself has changed, we may find that we can no longer adapt to it. There were times when researchers could do whatever they wanted in the past, but now is the time when the entire society must get involved. Under a social consensus, we must think and act. Thank you very much.

(This interview was held at the AIST Akihabara Office in Chiyoda-ku, Tokyo, on July 2, 2010.)

Profile of Dr. Teruhiko Higuchi
Graduated from the School of Medicine, The University of Tokyo in 1972. Worked at the University of Tokyo Hospital; Saitama Medical University; Psychiatry and Human Behavior Department, Graduate School of Medicine, Gunma University; and as the professor of the Department of Psychiatry and Neurology, Showa University Fujigaoka Hospital. Became the deputy director of the Kohnodai Hospital, NCNP in 1999, and its director the following year. Became the director of the Musashi Hospital, NCNP (currently National Center Hospital) in 2004; the president of the NCNP from 2007 to present. Member of the Science Council of Japan. Also member of the Japan Society of Clinical Neuropsychopharmacology (vice president), Japan Society for Occupational Mental Health (permanent director), Japanese Society of Mood Disorders (director), and others. Specialties are pharmacology and biochemistry of mood disorders, clinical psychopharmacology, and clinical research of depression.

Editorial Policy

Synthesiology Editorial Board

Objective of the journal

The objective of *Synthesiology* is to publish papers that address the integration of scientific knowledge or how to combine individual elemental technologies and scientific findings to enable the utilization in society of research and development efforts. The authors of the papers are researchers and engineers, and the papers are documents that describe, using "scientific words", the process and the product of research which tries to introduce the results of research to society. In conventional academic journals, papers describe scientific findings and technological results as facts (i.e. factual knowledge), but in *Synthesiology*, papers are the description of "the knowledge of what ought to be done" to make use of the findings and results for society. Our aim is to establish methodology for utilizing scientific research result and to seek general principles for this activity by accumulating this knowledge in a journal form. Also, we hope that the readers of *Synthesiology* will obtain ways and directions to transfer their research results to society.

Content of paper

The content of the research paper should be the description of the result and the process of research and development aimed to be delivered to society. The paper should state the goal of research, and what values the goal will create for society (Items 1 and 2, described in the Table). Then, the process (the scenario) of how to select the elemental technologies, necessary to achieve the goal, how to integrate them, should be described. There should also be a description of what new elemental technologies are required to solve a certain social issue, and how these technologies are selected and integrated (Item 3). We expect that the contents will reveal specific knowledge only available to researchers actually involved in the research. That is, rather than describing the combination of elemental technologies as consequences, the description should include the reasons why the elemental technologies are selected, and the reasons why new methods are introduced (Item 4). For example, the reasons may be: because the manufacturing method in the laboratory was insufficient for industrial application; applicability was not broad enough to stimulate sufficient user demand rather than improved accuracy; or because there are limits due to current regulations. The academic details of the individual elemental technology should be provided by citing published papers, and only the important points can be described. There should be description of how these elemental technologies are related to each other, what are the problems that must be resolved in the integration process, and how they are solved (Item 5). Finally, there should be descriptions of how closely the goals are achieved by the products and the results obtained in research and development, and what subjects are left to be accomplished in the future (Item 6).

Subject of research and development

Since the journal aims to seek methodology for utilizing the products of research and development, there are no limitations on the field of research and development. Rather, the aim is to discover general principles regardless of field, by gathering papers on wide-ranging fields of science and technology. Therefore, it is necessary for authors to offer description that can be understood by researchers who are not specialists, but the content should be of sufficient quality that is acceptable to fellow researchers.

Research and development are not limited to those areas for which the products have already been introduced into society, but research and development conducted for the purpose of future delivery to society should also be included.

For innovations that have been introduced to society, commercial success is not a requirement. Notwithstanding there should be descriptions of the process of how the technologies are integrated taking into account the introduction to society, rather than describing merely the practical realization process.

Peer review

There shall be a peer review process for *Synthesiology*, as in other conventional academic journals. However, peer review process of *Synthesiology* is different from other journals. While conventional academic journals emphasize evidential matters such as correctness of proof or the reproducibility of results, this journal emphasizes the rationality of integration of elemental technologies, the clarity of criteria for selecting elemental technologies, and overall efficacy and adequacy (peer review criteria is described in the Table).

In general, the quality of papers published in academic journals is determined by a peer review process. The peer review of this journal evaluates whether the process and rationale necessary for introducing the product of research and development to society are described sufficiently well.

In other words, the role of the peer reviewers is to see whether the facts necessary to be known to understand the process of introducing the research finding to society are written out; peer reviewers will judge the adequacy of the description of what readers want to know as reader representatives.

In ordinary academic journals, peer reviewers are anonymous for reasons of fairness and the process is kept secret. That is because fairness is considered important in maintaining the quality in established academic journals that describe factual knowledge. On the other hand, the format, content, manner of text, and criteria have not been established for papers that describe the knowledge of “what ought to be done.” Therefore, the peer review process for this journal will not be kept secret but will be open. Important discussions pertaining to the content of a paper, may arise in the process of exchanges with the peer reviewers and they will also be published. Moreover, the vision or desires of the author that cannot be included in the main text will be presented in the exchanges. The quality of the journal will be guaranteed by making the peer review process transparent and by disclosing the review process that leads to publication.

Disclosure of the peer review process is expected to indicate what points authors should focus upon when they contribute to this journal. The names of peer reviewers will be published since the papers are completed by the joint effort of the authors and reviewers in the establishment of the new paper format for *Synthesiology*.

References

As mentioned before, the description of individual elemental technology should be presented as citation of papers published in other academic journals. Also, for elemental technologies that are comprehensively combined, papers that describe advantages and disadvantages of each elemental technology can be used as references. After many papers are accumulated through this journal, authors are recommended to cite papers published in this journal that present similar procedure about the selection of elemental technologies and the introduction to society. This will contribute in establishing a general principle of methodology.

Types of articles published

Synthesiology should be composed of general overviews such as opening statements, research papers, and editorials. The Editorial Board, in principle, should commission overviews. Research papers are description of content and the process of research and development conducted by the researchers themselves, and will be published after the peer review process is complete. Editorials are expository articles for science and technology that aim to increase utilization by society, and can be any content that will be useful to readers of *Synthesiology*. Overviews and editorials will be examined by the Editorial Board as to whether their content is suitable for the journal. Entries of research papers and editorials are accepted from Japan and overseas. Manuscripts may be written in Japanese or English.

Required items and peer review criteria (January 2008)

	Item	Requirement	Peer Review Criteria
1	Research goal	Describe research goal (“product” or researcher’s vision).	Research goal is described clearly.
2	Relationship of research goal and the society	Describe relationship of research goal and the society, or its value for the society.	Relationship of research goal and the society is rationally described.
3	Scenario	Describe the scenario or hypothesis to achieve research goal with “scientific words”.	Scenario or hypothesis is rationally described.
4	Selection of elemental technology(ies)	Describe the elemental technology(ies) selected to achieve the research goal. Also describe why the particular elemental technology(ies) was/were selected.	Elemental technology(ies) is/are clearly described. Reason for selecting the elemental technology(ies) is rationally described.
5	Relationship and integration of elemental technologies	Describe how the selected elemental technologies are related to each other, and how the research goal was achieved by composing and integrating the elements, with “scientific words”.	Mutual relationship and integration of elemental technologies are rationally described with “scientific words”.
6	Evaluation of result and future development	Provide self-evaluation on the degree of achievement of research goal. Indicate future research development based on the presented research.	Degree of achievement of research goal and future research direction are objectively and rationally described.
7	Originality	Do not describe the same content published previously in other research papers.	There is no description of the same content published in other research papers.

Instructions for Authors

Synthesiology Editorial Board
Established December 26, 2007
Revised June 18, 2008
Revised October 24, 2008
Revised March 23, 2009
Revised August 5, 2010

1 Types of contributions

Research papers or editorials and manuscripts to the "Readers' Forum" should be submitted to the Editorial Board. After receiving the manuscript, if the editorial board judges it necessary, the reviewers may give an interview to the author(s) in person or by phone to clarify points in addition to the exchange of the reviewers' reports.

2 Qualification of contributors

There are no limitations regarding author affiliation or discipline as long as the content of the submitted article meets the editorial policy of *Synthesiology*, except authorship should be clearly stated. (It should be clearly stated that all authors have made essential contributions to the paper.)

3 Manuscripts

3.1 General

3.1.1 Articles may be submitted in Japanese or English. Accepted articles will be published in *Synthesiology* (ISSN 1882-6229) in the language they were submitted. All articles will also be published in *Synthesiology - English edition* (ISSN 1883-0978). The English edition will be distributed throughout the world approximately four months after the original *Synthesiology* issue is published. Articles written in English will be published in English in both the original *Synthesiology* as well as the English edition. Authors who write articles for *Synthesiology* in Japanese will be asked to provide English translations for the English edition of the journal within 2 months after the original edition is published.
3.1.2 Research papers should comply with the structure and format stated below, and editorials should also comply with the same structure and format except subtitles and abstracts are unnecessary. Manuscripts for "Readers' Forum" shall be comments on or impressions of articles in *Synthesiology*, or beneficial information for the readers, and should be written in a free style of no more than 1,200 words. Editorials and manuscripts for "Readers' Forum" will be reviewed by the Editorial Board prior to being approved for publication.
3.1.3 Research papers should only be original papers (new literary work).
3.1.4 Research papers should comply with various guidelines of research ethics.

3.2 Structure

3.2.1 The manuscript should include a title (including subtitle), abstract, the name(s) of author(s), institution/contact, main text, and keywords (about 5 words).
3.2.2 Title, abstract, name of author(s), keywords, and institution/contact shall be provided in Japanese and English.
3.2.3 The manuscript shall be prepared using word processors or similar devices, and printed on A4-size portrait (vertical) sheets of paper. The length of the manuscript shall be, about 6 printed pages including figures, tables, and photographs.
3.2.4 Research papers and editorials shall have front covers and the category of the articles (research paper or editorial) shall be stated clearly on the cover sheets.
3.2.5 The title should be about 10-20 Japanese characters (5-10 English words), and readily understandable for a diverse readership background. Research papers shall have subtitles of about 15-25 Japanese characters (7-15 English words) to help recognition by specialists.
3.2.6 The abstract should include the thoughts behind the integration of technological elements and the reason for their selection as well as the scenario for utilizing the research results in society.
3.2.7 The abstract should be 300 Japanese characters or less (125 English words). The Japanese abstract may be omitted in the English edition.
3.2.8 The main text should be about 9,000 Japanese characters (3,400 English words).
3.2.9 The article submitted should be accompanied by profiles of all authors, of about 200 Japanese characters (75 English words) for each author. The essential contribution of each author to the paper should also be included. Confirm that all persons who have made essential contributions to the paper are included.
3.2.10 Discussion with reviewers regarding the research paper content shall be done openly with names of reviewers disclosed, and the Editorial Board will edit the highlights of the review process to about 3,000 Japanese characters (1,200 English words) or a maximum of 2 pages. The edited discussion will be attached to the main body of the paper as part of the article.

3.2.11 If there are reprinted figures, graphs or citations from other papers, prior permission for citation must be obtained and should be clearly stated in the paper, and the sources should be listed in the reference list. A copy of the permission should be sent to the Publishing Secretariat. All verbatim quotations should be placed in quotation marks or marked clearly within the paper.

3.3 Format

3.3.1 The headings for chapters should be 1, 2, 3…, for subchapters, 1.1, 1.2, 1.3…, for sections, 1.1.1, 1.1.2, 1.1.3.
3.3.2 The text should be in formal style. The chapters, subchapters, and sections should be enumerated. There should be one line space before each paragraph.
3.3.3 Figures, tables, and photographs should be enumerated. They should each have a title and an explanation (about 20-40 Japanese characters or 10-20 English words), and their positions in the text should be clearly indicated.
3.3.4 For figures, clear originals that can be used for printing or image files (resolution 350 dpi or higher) should be submitted. In principle, the final print will be 15 cm × 15 cm or smaller, in black and white.
3.3.5 For photographs, clear prints (color accepted) or image files should be submitted. Image files should specify file types: tiff, jpeg, pdf, etc. explicitly (resolution 350 dpi or higher). In principle, the final print will be 7.2 cm × 7.2 cm or smaller, in black and white.
3.3.6 References should be listed in order of citation in the main text.

Journal – [No.] Author(s): Title of article, *Title of journal* (italic), Volume(Issue), Starting page-Ending page (Year of publication).

Book – [No.] Author(s): *Title of book* (italic), Starting page-Ending page, Publisher, Place of Publication (Year of publication).

4 Submission

One printed copy or electronic file of manuscript with a checklist attached should be submitted to the following address:

Synthesiology Editorial Board
c/o Website and Publication Office, Public Relations Department, National Institute of Advanced Industrial Science and Technology (AIST)
Tsukuba Central 2, 1-1-1 Umezono, Tsukuba 305-8568
E-mail: synthesiology@m.aist.go.jp

The submitted article will not be returned.

5 Proofreading

Proofreading by author(s) of articles after typesetting is complete will be done once. In principle, only correction of printing errors are allowed in the proofreading stage.

6 Responsibility

The author(s) will be solely responsible for the content of the contributed article.

7 Copyright

The copyright of the articles published in “*Synthesiology*” and “*Synthesiology English edition*” shall belong to the National Institute of Advanced Industrial Science and Technology (AIST).

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Letter from the editor

Three years have passed since the launch of *Synthesiology* Volume 1 Issue 1 in January 2008. To present, we have published twelve issues featuring over seventy research papers and over ten articles and discussions. The Editorial Board is grateful to the readers who have shown great interest in and offered encouragement to *Synthesiology*.

Synthesiology has mainly carried papers of AIST and universities, but in this issue, we published our first research paper on corporate development, “How the car navigation system was put to practical use”. The car navigation system was pioneered in Japan, and this technology has contributed to the safety and convenience of people around the world. This paper is a clear narrative of the R&D scenario and processes in its early phase of development.

In this paper, the processes whereby the diverse elemental technologies crossing over various fields are integrated to attain the goal are explained. It is also valuable since it allows us to look at the decision-making processes in a case of corporate R&D. It is certainly an interesting piece not only for corporate researchers and engineers but also for researchers of public institutes and universities. I strongly recommend people to read it.

The research paper “Investigation of the distribution of elements in the whole of Japan and their applications” is a comprehensive geological study that was conducted for over twenty years. The geochemical map for the whole of Japan was published for the first time, and this is an example of rigorous synthetic research accomplished by integrating multiple elemental technologies while establishing the basic research methodology. Also, the research paper “R&D of SiC semiconductor power devices and strategy towards their practical utilization” is an informative one that describes how the research strategy has evolved according to the changes in situations over the fifteen years of technology that is now ready to be put to practical use.

In medical research, Japan, compared to other advanced countries, is considered to be significantly behind in clinical medicine as opposed to basic medicine. Since clinical research is related directly to the diagnosis and treatment of diseases, there are many points in common with *Type 2 Basic Research* of *Synthesiology*. In an interview with President Higuchi of the National Center for Neurology and Psychiatry, we discussed the position Japan should assume for this type of research.

For the third anniversary of *Synthesiology*, I am thankful to the researchers and engineers of various fields for maintaining their interest. The “Discussions with Reviewers” that was introduced as a new attempt by *Synthesiology* has been highly acclaimed by the readers, and we will continue disclosing this reviewing processes in the future issues. We are waiting for submissions to this journal by researchers and engineers of wide-ranging fields who engage in R&D of science and technology looking for an outlet to society.

Editor in Chief
Akira Ono

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"Synthesiology-English edition" is a translated version of "Synthesiology", which is published quarterly, ISSN 1882-6229, by AIST. Papers or articles published in "Synthesiology-English edition" appear approximately four months after the publication of the original "Synthesiology".

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