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English edition

Developing a leading practical application for 3D IC chip stacking technology

Securing a stable supply of critical raw metals

Scenario in synthetic-type research: its role and description

Consortium style study on the development of highly reliable photovoltaic modules and acceleration test methods

Synthesiology editorial board

2016

1

Highlights of the Papers in *Synthesiology* Volume 9 Issue 1 (Japanese version Feb. 2016)

Synthesiology is a journal that describes the objectives and social value of research activities that attempt to utilize the results in society, the specific scenarios and research procedures, and the process of synthesis and integration of elemental technologies. To allow the readers to see the value of the papers in a glance, the highlights of the papers characteristic to *Synthesiology* are extracted and presented by the Editorial Board.

***Synthesiology* Editorial Board**

Developing a leading practical application for 3D IC chip stacking technology
— How to progress from fundamental technology to application technology —
While high integration of integrated circuits had been achieved by downsizing the elements, the achievement of three-dimensionality had not been the main topic of R&D due to its technological difficulties. However, the limit of downsizing has been recognized in recent years, and 3D stacking technology has gained attention. Aoyagi *et al*. draw the scenario for the development of 3D IC chip stacking technology, and describe the elemental technologies (TSV, cone-shaped bumps) to achieve the goal of the scenario, and the results of the integrated design technology. This is a chronological presentation of their efforts on the strategy to efficiently use the limited research resources through prioritization of issues and obtainment of research resources.

Securing a stable supply of critical raw metals
— Efforts and issues for the securement of rare-earth resources —
With the crises arising from the soaring prices of metal resources due to the economic growth of the emerging industrial nations and from the export regulation of rare earths by China, Takagi *et al*. of the Mineral Resources Research Group responded to the demands for finding prospective deposits, preparing a mineral processing test base, constructing a database, and building cooperative relationship with overseas geological survey institutions, in their effort to organize geological information and to help the government maintain a stable supply of rare metal resources. In this paper, AIST's R&D, collaboration with resource-producing countries, joint research with development organizations that are necessary for resource development are described with specific case studies. This is a paper that overviews the process of rare earth resource research.

Scenario in synthetic-type research: its role and description
— An investigation from Synthesiology papers —
Innovation that originates from the results of basic research is the mainstream of modern R&D, and such innovation is expected to solve various problems in society and to bring about sustainable prosperity. As research funds are allotted and researchers spend effort to obtain results, one problem arises. The problem is that the process, by which basic research leads to results that are useful in solving social problems, is unclear. As a result, the researcher working on the process seeks all sorts of possibilities, and approaches the set solution sometimes by intuition, sometimes by comprehensive thinking, and either way by trial and error. There is a unique research methodology, although still not clarified, called *Type Two Basic Research*, and its results are the papers of *Synthesiology*. The objective of this journal is to publish the results and to clarify this research methodology.

This paper is a study to extract a common method that lies behind the diverse types of research that has not become apparent yet, by studying over 100 papers that have been published in eight years since the launch of the journal. As a characteristic of *Type Two Basic Research* that is a synthetic-type research, attention was paid to the scenario that appears in each paper and serves as the core of research. It is shown that the logical characteristic of the scenarios is common, and the characteristic of the synthetic-type research is presented in a structural manner. This is a valuable paper that shows that the scenario can be explicitly expressed by verbal expression and diagrams, and that it is possible to substantiate research for extracting the theory of research. This paper is beneficial for the future *Type Two Basic Research*, and offers useful insight to the direction of research for extracting methodologies.

Consortium style study on the development of highly reliable photovoltaic modules and acceleration test methods
— Management of the "Consortium Study on Fabrication and Characterization of Solar Cell Modules with Long Life and High Reliability" —
In establishing and managing a consortium for photovoltaic modules, it was considered at the time that reliability evaluation technologies were insufficient by the academia and industry, and therefore, it was necessary to establish reliability evaluation technology based on scientific findings by organizing a prototype line for photovoltaic modules. This article specifically describes the process by which sufficient discussions were held with participating companies to obtain understanding when setting research topics and management policies of the consortium, so that the consortium could become a place where several companies cooperate in the development of common fundamental technology. Pertaining to reliability evaluation technology that is the core, the point that should be evaluated highly is the establishment of the acceleration test method through research backed by scientific evidence that replaces know-how and experiences. This successful case will have major ripple effect on other fields.

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Synthesiology – English edition Vol.9 No.1 (Jun. 2016)

Contents

Developing a leading practical application for 3D IC chip stacking technology

— How to progress from fundamental technology to application technology —

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[Translation from *Synthesiology*, Vol.9, No.1, p.1-14 (2016)]

3D IC chip stacking technology, which is a technology to vertically stack multiple IC chips such as CMOS, MEMS and power IC chips, is expected to be one of future electronic device integration technologies, because integration along the additional vertical dimension affords efficient use of space and innovation of system architecture. We developed fundamental technology of high density integration for 3D IC chip stacking. To accelerate industrial applications of this technology, a mass-production process was developed in collaboration with a manufacturing equipment company.

Keywords : Semiconductor device, IC, 3D stacking, packaging, TSV

1 Introduction

The electronic devices that evolved using semiconductor integration devices as core parts were commercialized for use in industrial devices, home electronic devices, and personal mobile electronic devices, through continuous technological development for increased performances such as achievement of small-size packaging, high-density integration, and low power consumption. They have spread throughout businesses, households, and on a personal level, and dramatic increase in the number of products was seen worldwide. By the end of 2014, the diffusion rate exceeded 100 %, where the number of mobile phone holders became larger than the number of the world population.[1]

The innovation that should be brought to attention in the history of semiconductor integrated device is the achievement of tolerance to large manufacturing variation in the property of elements. Wide margin of operability was obtained compared to other device structures through the employment of complementary metal oxide semiconductor (CMOS) transistor device structure, where the n-channel and p-channel MOS transistors are paired together. This enabled the realization of an integrated circuit (IC) with over one billion transistors integrated on a chip.[2]

On the other hand, various limiting factors such as the size reduction limit of microfabrication and increased manufacturing costs became apparent for the semiconductor IC technologies, and the attempt to increase the integration density seemed to face the limit. The three-dimensional IC chip stacking technology whereby the IC devices are stacked vertically and packaged is one of the solutions, and expectation for it is rising recently as a technology for semiconductor device stacking that enables the increase of integration density for semiconductor ICs. Therefore, we established the fundamental technology for high-density high-integration electronic hardware construction required for 3D IC chip stacking, and we are working on the R&D of the application phase to create the flow of application system development, while engaging in technical support of mass-production technology that, in practice, should be undertaken by leading companies.

2 Advancement of electronic hardware system integration technology by 3D IC chip stacking and the goal of this research

First, we shall review the recent development trends of the electronic hardware system integration technology that advanced the manufacturing technology in response to the demand for high density and high integration to enhance the system performance. The system integration method called the system in package (SIP)[Term 1] is gaining attention, where several IC chips are stacked in a semiconductor IC package to integrate them into a certain size electronic system. This method enables stacking in the vertical direction that is different from the planar integration technology of

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the ordinary semiconductor IC.[3] The R&D for the SIP method has been conducted actively at a practical level for downsizing, speed increase, and low power consumption in mobile electronic devices, and the method has been incorporated into actual products. SIP is one of system integration technologies called “more than Moore” to achieve integration in the vertical direction that is on a different dimension from Moore’s Law that presents the proportional reduction of device size. It is thought to be complementary with the system integration method called the system on chip (SOC)[Term 2] where a certain size electronic system is embedded on an IC chip. However, the interconnections between the IC chips are done with relatively long wires including bonding wires and internal wiring in a package, and such structure is not suitable for high-speed or high-frequency operation. On the other hand, the 3D IC chip stacking technology, which is the technology to vertically stack multiple IC chips by forming micro-bump joints and through-Si-via (TSV)[Term 3] electrodes penetrate the substrate of the IC chip from surface to the back side, is highly expected as the technology that can achieve diverse high performances such as downsizing, high density, high speed, high performance, and low power consumption in electronic hardware.[4]-[6] It should be noted that the 3D IC chip stacking can respond to high-density integration of IC devices using different substrate materials and processes for which realization is difficult by SOC method. By extending the wiring space in the hardware from 2D to 3D, there is possibility for major changes in the configuration of the circuit and the system.

To realize a specific high-performance electronic device where the 3D IC chip stacking technology is applied at system level as a fundamental technology for high-density high-integration electronic hardware configuration, it is necessary to develop a prototyping technology of the 3D IC chip stacking system. By developing innovative circuit and system technology that thoroughly utilizes the merits of 3D IC chip stacking, it becomes possible to send out a next-generation hardware system integration technology into society.

Because the R&D items required for the realization of 3D IC chip stacking system spread across extremely diverse and multifarious technological fields, not all can be covered within the limited research resource at AIST. Therefore, we followed a scenario of engaging primarily in the technical issues in which the companies have fallen behind, yet are very important and very urgent, and we have engaged in the R&D for establishing fundamental technology for 15 years.

Figure 1 shows the progress so far of the electronic hardware system integration technology. First, the SOC technology that enables achievement of a high-performance system is a technology for integrating several circuit blocks that configure a certain size electronic system onto a large-scale IC chip. Compared to conventional large-scale IC development and manufacturing, the cost increases significantly due to the longer time required for SOC development and manufacturing. SOC commercial products will be hard to realize unless there is an IC chip that can be utilized in several commercial system products through a general-purpose circuit design and for which large-scale production over several million units is possible (such as in high-functional general-purpose CPUs[Term 4] and general-purpose image processors). Second, the SIP technology that allows compact integration of multiple IC chips is a technology to integrate multiple IC chips corresponding to the circuit block that configures the system into one package, and it is widely used as it allows significant reduction of development

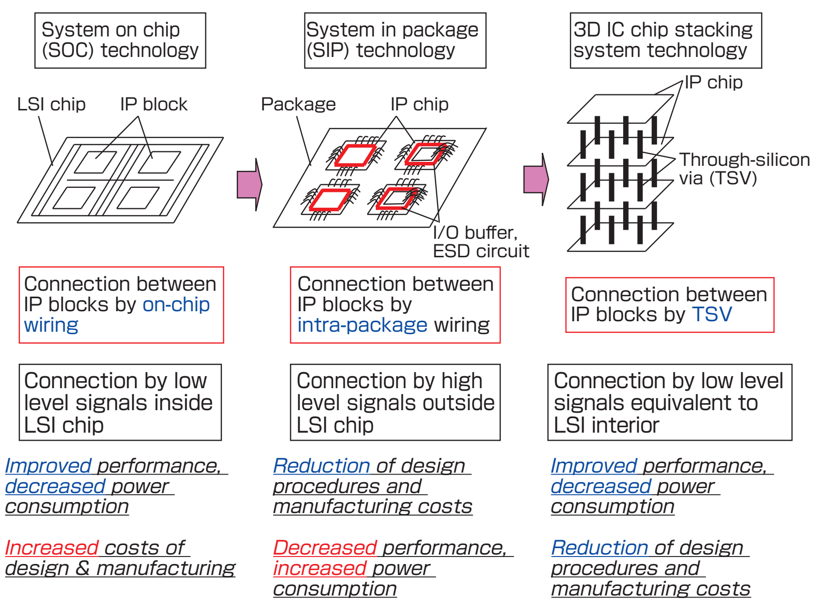

Fig. 1 Progress of electronic hardware system integration technology

and manufacturing costs in the consumer application fields that do not demand much high performance. Third, the 3D IC chip stacking technology, which uses TSVs and bump joints and is also called the ultimate SIP technology, is a technology that allows performance equivalent to SOC or even surpassing SOC by adopting a novel system architecture utilizing 3D wiring topology. There is a possibility for the significant reduction of its development and manufacture costs compared to SOC.[7] Against the sharp increase of cost for achieving nano-size device structure expected for next-generation nodes, improvement of the integration level while keeping down the total cost through 3D stacking is expected.

The merit for using the 3D IC chip stacking technology in digital systems is that increased system processing performance can be expected by employing the parallel processing architecture by multi-layering the functional circuit blocks such as the multi-core architecture.[8] To achieve this concept, the important key subject is to significantly raise the data communication capacity between the processing blocks. From this perspective, Fig. 2 shows the categorization of the IC chip stacking technology according to the signal transmission method between the chips embedded with processing IP[Term 5] blocks (called IP chips) that conducts various arithmetic logic processing. The chip stacking method by thin IC package stacking is appropriate for the construction of a general-purpose small system with emphasis on low cost. On the other hand, the chip stacking method by wireless connection using capacitive, inductive, or electromagnetic coupling is suitable for the construction of a robust system that requires high-speed transmission and high reliability due to avoiding physical connection. Also, the chip stacking method by a through Si via (TSV) that penetrates the substrate of the IC chip is suitable for the construction of high-performance low-cost systems using several TSVs. The chip stacking methods by optical waveguide connection using the optoelectronic packaging technology and silicon photonics[Term 6] technology are suitable for the construction of high end systems such as core networks and supercomputers that demand maximum level performance.

In this research, the final outcome is set as the preparation of the R&D environment for design, prototyping, and evaluation of the practical hardware system using the 3D IC chip stacking technology, that are necessary to widely diffuse into society, as well as the verification of typical prototype application system that takes advantage of the 3D IC chip stacking.

3 Manufacturing process for the 3D IC chip stacking and preparation of the total design environment

3.1 Elemental technologies for the manufacturing process of the 3D IC chip stacking

Since the corporate R&D engineers pay attention to the new method as a way to increase the degree of integration in semiconductor devices, engaging in the development of 3D IC chip stacking process at the wafer level, even in the R&D phase, would be the general approach, assuming the progression to the mass production process.[9]-[15] However, though it may seem to be a long route to take, AIST has engaged in the R&D aiming for the construction of a highly efficient rapid prototyping environment, and concentrating on the 3D IC chip stacking process at chip level that enables manufacturing at high yield and short production time using the low-cost process devices. Particularly, the 3D IC stacking and packaging process at chip level is highly compatible with the minimal fab[Term 7] concept proposed by AIST as a semiconductor device manufacturing system using small 0.5-inch size Si wafers, and we shall emphasize the possibility of constructing a minimal 3D stacking process line that

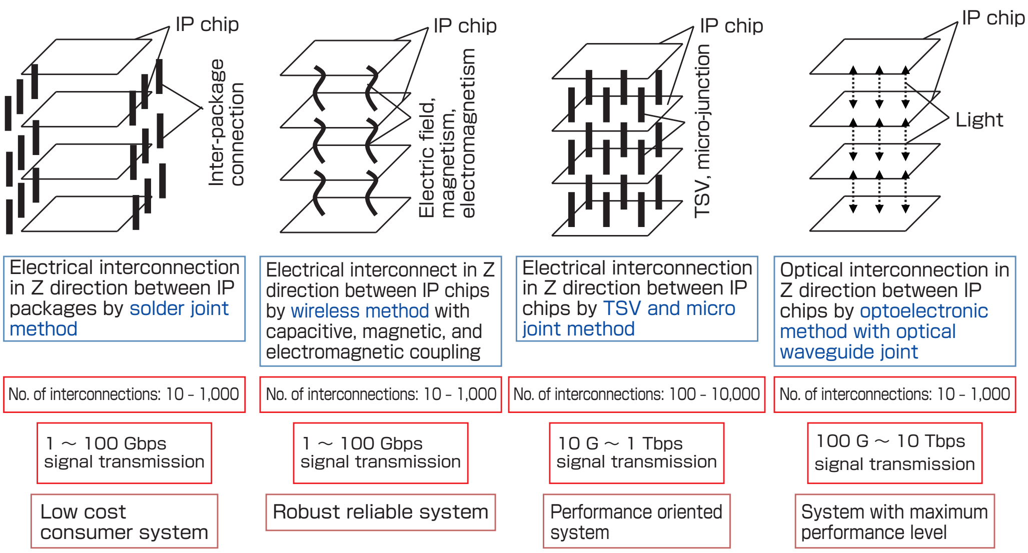

Fig. 2 3D IC chip stacking system technology

includes all manufacturing processes from semiconductor IC device manufacture to stacking and packaging.[16]

In the general 3D IC stacking manufacturing process, the process flow is as follows: the deep embedded through Si substrate via electrodes are formed from the surface toward the back side after a regular CMOS semiconductor manufacturing process, the silicon substrate is thinned from the back side to expose the bottom of the via hole electrodes, wiring is formed on the back side, the metal micro-bumps are formed on the wiring using soldering material, and the bump joints are formed between the stacked devices using high-precision bonding technology. In this manufacturing process flow, the process of forming the through-silicon-via (TSV) electrode that penetrates the silicon substrate is the core process from the points of difficulty and cost. Specifically, as shown in Fig. 3, it is a series of processes where the deep through via holes are etched by the Bosch method from the surface to the back side of the silicon substrate, the via holes are filled with metal by an electroplating process after forming barrier and insulating layers on the wall of the via holes by the CVD method, the electrodes are exposed on the surface by a smoothing technique such as the CMP method, and further thinning is done from the back side by grinding, CMP, and RIE methods to expose the electrodes at the bottom of the via holes to form completely penetrating electrodes.

Figure 4 lists the development items of the fundamental technologies (process and evaluation) of the 3D IC chip stacking system integration that were developed at AIST. The specific items include the following. Elemental technologies for chip stacking process are the following: low-volume, low-resistance, and low internal stress TSV structure using low-k organic insulator;[17] micro-pitch, high-density, and micro-bump connection formed by a thermo-compression method using cone-shaped micro-bumps;[18]-[20] electroless plating connection for power source pads where the power source pad electrodes

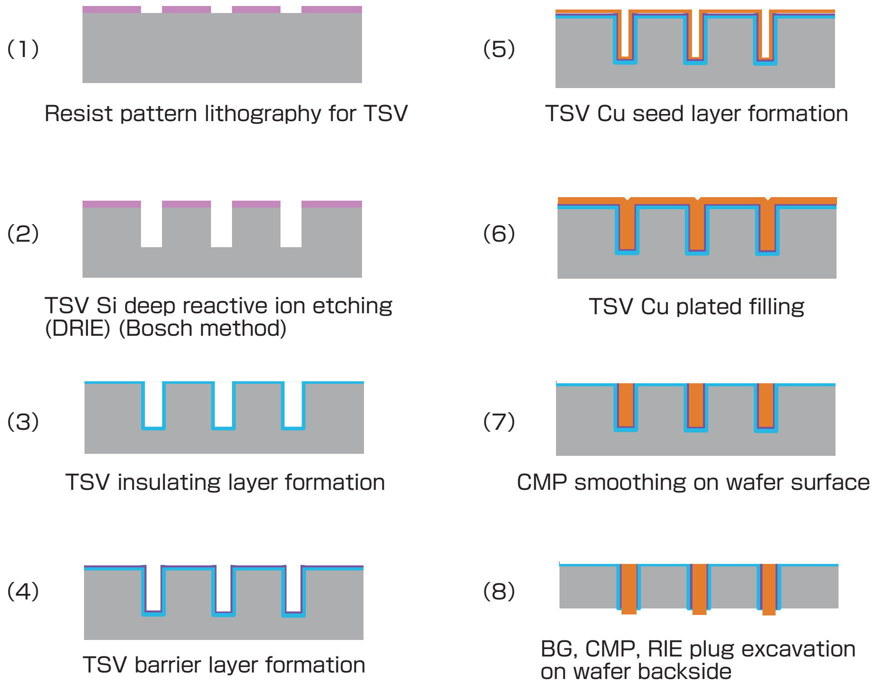

Fig. 3 Process flow for manufacturing the TSV

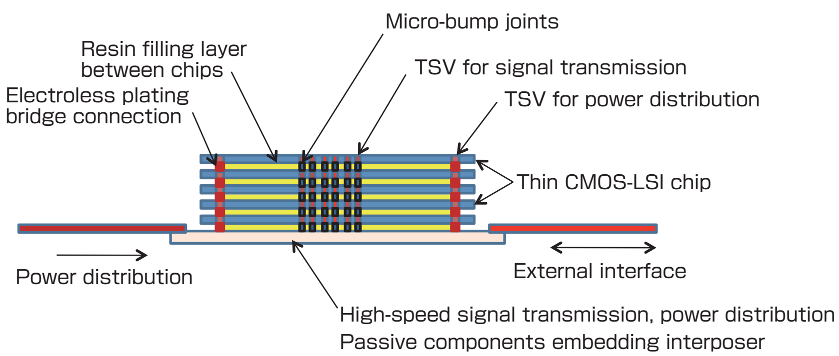

Fig. 4 Fundamental technologies for the 3D IC chip stacking system integration (stacking process and evaluation test)

are connected by direct Ni-B and Au electroless plating after chip stacking;[21][22] interposer with passive components where the thin film capacitors or the chip capacitors are embedded in the substrate;[23][24] and others. Evaluation and inspection technologies are as follows: evaluation of electrical property in local fine structures using high-speed sharp step signals with 10-ps rising time;[25] evaluation of 20 Gbps high-speed digital signal transmission;[26] evaluation of power supply wiring impedance using impedance analyzer for 10 Hz - 40 GHz super-wide bandwidth;[27] inspection of good chips where electrical testing can be done at chip level using the membrane fine pitch contact probe;[28] boundary scan embedded test circuit where total electrical connection test of fine interconnects can be conducted after stacking;[29] high-speed inspection of cone-shape micro-bumps where wafer level shape optical inspection can be conducted by laser illumination and high-speed high-resolution image sensors;[30] and others.

As an example of the development of a low-volume, low-resistance, and low internal stress TSV structure, we describe the development of a TSV structure using the parylene organic resin as the insulating layer of the TSV sidewall.[17] Figure 5 shows the manufacturing process flow of the TSV structure with parylene sidewall insulating layer, where the uniform parylene thin film was formed using low-temperature CVD method. Figure 6 shows the cross-sectional SEM photograph after the formation of a parylene sidewall insulating layer in the TSV manufacturing process. Compared to the sidewall insulating layer made of inorganic insulating materials such as SiO_2 or SiN_x, good coverage with uniform and thick parylene film can be achieved. Figure 7 shows the cross-sectional SEM photograph after parylene sidewall insulating layer formation and Cu plating in the TSV manufacturing process. The filling of TSV holes with Cu metal can be done by the Cu electroplating method. For suppressing the internal stress produced around the sidewall insulating layer due to the different thermal expansion coefficient of Cu and Si, the internal stress relaxation in the Si substrate can be achieved due to the elastic deformation of the parylene film.

Next, as an example of the development of fine-pitch high-density micro-bump interconnections, we describe cone-shaped micro-bump interconnections formed by the nanoparticle deposition (NPD) method.[19] Figure 8 shows the SEM observation photograph of the cone-shaped gold (Au)

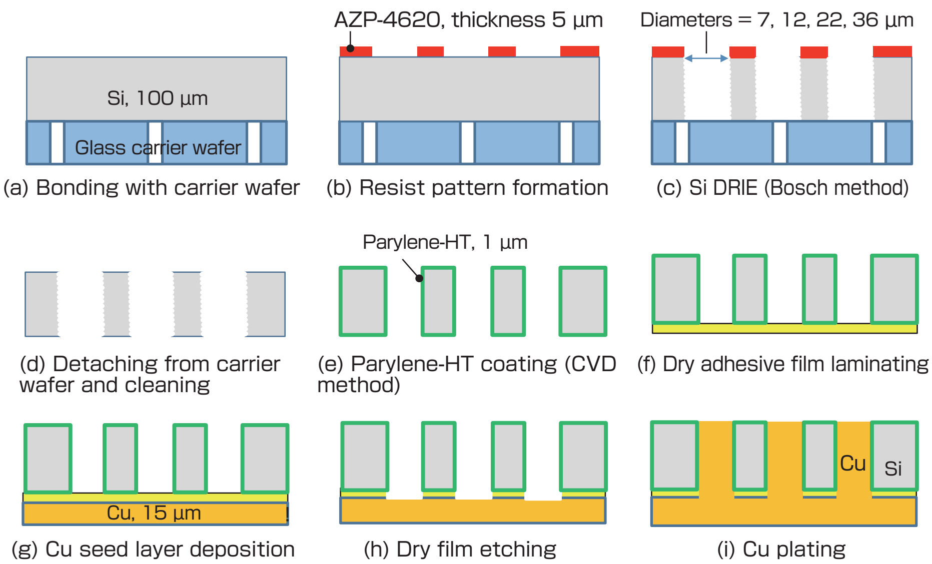

Fig. 5 Process flow for manufacturing the parylene sidewall insulating layer TSV structure

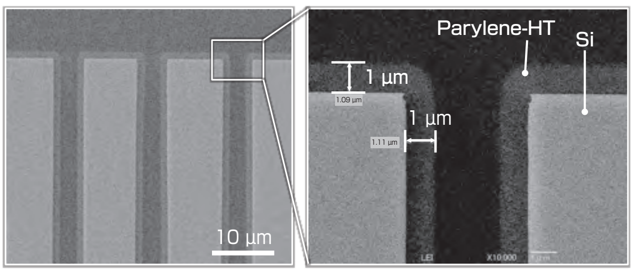

Fig. 6 Cross-sectional SEM photograph after the formation of parylene sidewall insulating layer in the TSV structure

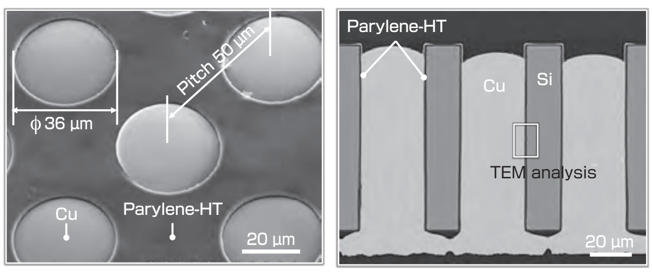

Fig. 7 Cross-sectional SEM photograph after Cu plating and filling of parylene sidewall insulating layer in the TSV structure

micro-bump array formed by the nanoparticle deposition method, where the Au nanoparticles are produced in the He gas atmosphere by an evaporating method, and the deposition is done by ejecting the He gas with the Au nanoparticles through a small bore nozzle. The cone-shaped micro-bumps have a diameter of 10 μm and a height of 12 μm, and are arranged in a 100 × 100 (10,000 bumps) array at a pitch of 20 μm. The cone-shaped Au bumps are formed with a self-assembly manner in a hole structure, as the film is formed as the substrate is scanned while the Au nanoparticles are sprayed from small bore nozzles, after the round hole photo resist mask is formed on the substrate, and at the same time, a peak structure grows at the upper end edge of the mask hole. Figure 9 shows the cross-sectional SEM photograph of one cone-shaped bump interconnection structure formed by the thermal compression method using a cone-shaped Au bump. By a thermo-compression process at temperature of 200 ºC, the bump height is compressed 44 % from 12.6 μm to 7.1 μm, and the 8.6 mΩ low-resistance connection can be achieved. The compression level can be controlled by the applied pressure.

By constructing the 3D IC chip stacking process environment at chip level, it is possible to meet the demand for rapid prototyping in the R&D phase. Also, through the construction of the multi-physics design and analysis environment, we are organizing the integrated analysis environment for multiple CAD tools where the electric, thermal, and mechanical properties can be comprehensively designed and analyzed in an integrated manner, as well as a seamless design environment where the design data can be handed over efficiently from upstream to downstream, or from IC device design to total system design. This will enable total integrated design in the final practical phase.

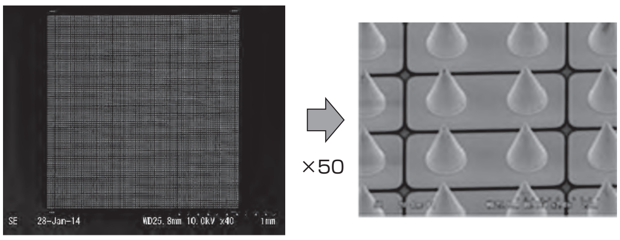

Fig. 8 SEM photograph of the 10,000 (100 x 100) cone-shaped Au micro-bump array (partially enlarged x50)
(Diameter: 10 μm, height: 12 μm, pitch: 20 μm)

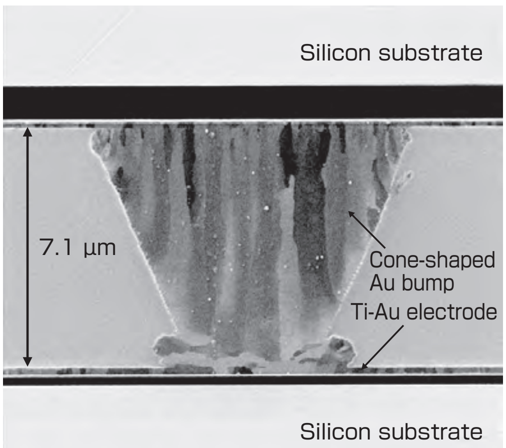

Fig. 9 Cross-sectional SEM photograph of the single cone-shaped bump connection structure

From the above development scenario, by using the physical hardware integration environment for the 3D IC chip stacking, we believe we can contribute to creating circuit and architecture technology with a completely new concept that cannot be realized with the conventional 2D IC. Specifically, by utilizing over 1,000 multi-channel electric connections among the stacked devices, we aim to produce a new system function that utilizes the high-capacity interface communication among the stacks.

3.2 Integration method in the 3D IC chip stacking system

In the design phase of the 3D IC chip stacking system, it is necessary to design a large-scale integrated circuit based on the 3D IC stack standard cell library that is the basic unit of design containing fine components (TSV electrode, metal micro-bump interconnection, inter-stack resin interfill, heat dissipation layer, etc.) with greatly varying properties (electric, thermal, mechanical, etc.). Therefore, it is necessary to design and make a prototype for the evaluation TEG[Term 8] device in varying designs with different design parameters, for the standard cells used as basic component units needed for design. Then, by comprehensively conducting property evaluations for electric, thermal, and mechanical properties, the 3D IC stacking design tool kit is prepared including a design guideline and design rules, not just the layout design library of the standard cells. By preparing the design tool kits through a series of tasks for design, prototyping, and evaluation using TEG or prototype devices repeated several times, we aim to achieve the matured level that ultimately enables design, prototyping, and evaluation of the practical system.

As an example of development of the IC design technology that coordinates electrical and thermal properties, we describe the development of an IC design flow constructed by introducing an IC thermal analysis software, based on the existing IC design tool.[31] Figure 10 shows the process flow of the IC thermal analysis in the electrothermal IC design. First, the conventional logic IC design tool is used for logic design simulation and circuit placement and wiring, and valuation is done by calculating the values of the average power consumption at a standard cell unit that is the basic unit of IC design, and then by allotting the values of consumed power to all transistors arranged in the cell. Based on the layout design data with allotted power consumption values, IC thermal analysis simulation is conducted using the transistor level thermal analysis software[32] that has been originally developed to enable efficient calculation. Figure 11 shows the flow of the thermally aware layout design data in electrothermal IC design using several design tools.

4 Verification R&D by design, prototyping, and evaluation using the TEG device for evaluation

The design and prototyping of evaluation TEG device will require funds in the hundred million yen range if conducted at wafer level, and this is not of the budget level of a research institute. On the other hand, using the shuttle service of the CMOS foundry where the design and prototyping of the CMOS semiconductor IC device at wafer level are conducted as shared multiple chip prototyping, the evaluation TEG device may be prototyped at one-tenth the required cost. We decided to conduct the R&D that assumes device prototyping using such a shuttle service.

For the IC device design, it is necessary to prepare a large-scale IC design CAD environment to conduct design independently, and that requires hundreds of millions of yen, and this cannot be undertaken easily by a laboratory. Authors Aoyagi and Nakagawa had used the CAD tool of Mentor Graphics Inc. 20 years ago to design the superconductor integrated circuit, but had to give up maintaining the tool environment since they were unable to pay the expensive licensing cost.

For the design, we decided to request cooperation of a fabless company that possessed a design environment and took design subcontracts. We searched for candidate companies,

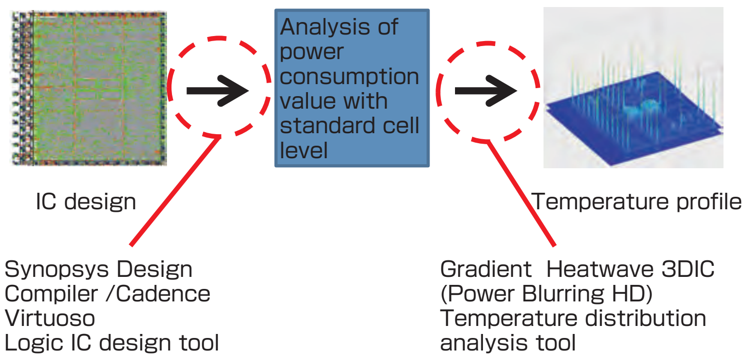

Fig. 10 Process flow for the IC thermal analysis in electrothermal IC design

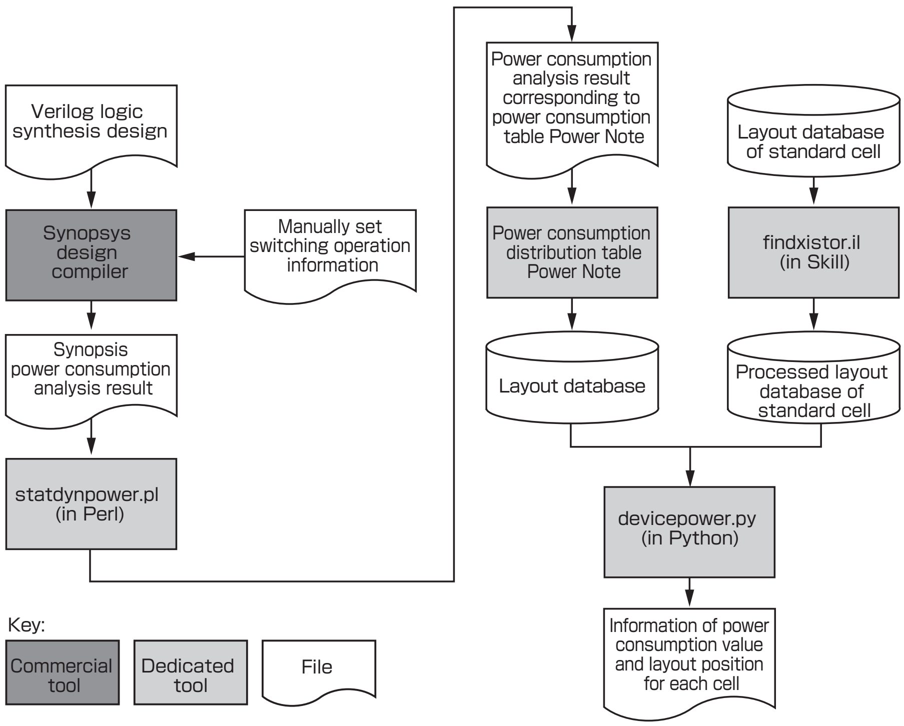

Fig. 11 Flow of design data for the thermal aware IC layout design regarding electrothermal IC design

and had a chance to meet Tops System Corporation that was established in our hometown Tsukuba in 1999.

In August 2007, the engineers of Tops System Corporation visited AIST to present the technologies for heterogeneous multi-core architecture TOPSTREAM that Tops System originally developed. We recognized the possibility that this may realize a new system design technology as the architecture was highly compatible with the 3D IC chip stacking system, and decided to collaborate.[33]

In 2008, the Supporting Grant for Small and Medium Enterprise from the Ministry of Economy, Trade and Industry was used to conduct the conceptual construction of the whole architecture including the IC stacking interface standard of Cool Interconnect, as the heterogeneous multi-core architecture for 3D IC chip stacking. Several patents were filed, and specific fundamental technology development was done for the stacking interface. For establishing the stacking interface, the IC device prototyping that required lots of resources was avoided, and the first priority was given to the construction of the communication protocol and testing technology for stacking interface where our developed technologies could be applied to file patents.[34] Figure 12 shows the concept of the Cool Interconnect. This is a wide bus bi-directional communication interface specification for stacked chips, where 1,600 10 μm diameter TSVs at 50 μm pitch were formed at the center of thin IC chips with 50 μm thickness, and eight layer chip stacking interconnected by micro-bumps is assured as maximum level.

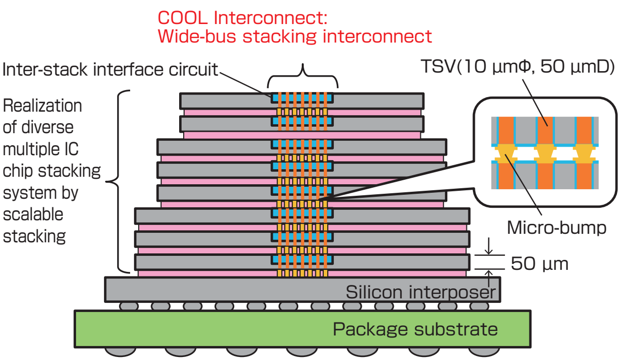

Fig. 12 Conceptual diagram of the Cool Interconnect

With the result of the conceptual investigation of the 3D IC stacking architecture including the stacking interface standard Cool Interconnect, we proposed a joint R&D project with Tops System Corporation for the R&D program of Innovative Energy-Saving Technology, New Energy and Industrial Technology Development Organization (NEDO) in May 2009. Fortunately, our proposal was selected, and through this NEDO R&D project, we were able to engage in the verification research of the 3D IC stacking architecture including the design and prototyping of the IC device. In this project, innovative energy-saving device technology that can achieve significant energy saving of the high-resolution image processing system through 3D IC stacking with heterogeneous multi-core architecture was developed. Figure 13 shows the concept on energy-saving in the 3D IC stacking system design using the Cool Interconnect.[35] This attempts to obtain sufficient power saving and high arithmetic logic operation performance by conducting efficient parallel processing using composite instructions, by reducing the clock frequency down to several 10 MHz and connecting the multiple diverse arithmetic logic processors through the Cool Interconnect.

We designed and prototyped the evaluation TEG consisting of a super-parallel bus interface circuit matching the 3D IC stacking, assuming the 1,600 TSVs and micro-bump interconnections based on the stacking interface standard Cool Interconnect. Then we evaluated the signal transmission property of 0.588 Gbps/1mW at low power consumption among the stacked devices connected face-to-face by micro-bumps. The stacking interface circuit was designed using the buffer and receiver circuits based on the

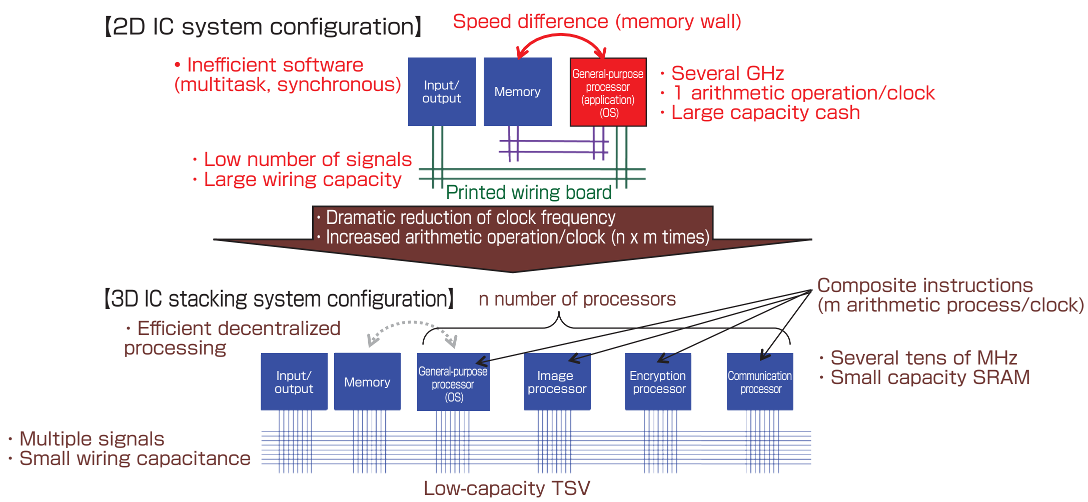

Fig. 13 Power saving in the 3D IC stacking system by Cool Interconnect

standard cells provided by CMOS device foundry, and high signal transmission capacity was realized by super-parallel interconnects without any special differential transmission circuits. For the formation of micro and low-capacitance TSV, in which the parasitic capacitance that affects the signal transmission property has been reduced, was designed and prototyped, and a low-capacitance property at 0.25 pF/TSV (2 pF even at eight stacks) was investigated for TSVs with a diameter of 10 μm and a depth of 50 μm by electrical evaluation. Unfortunately, the signal transmission property after stacking including the TSV could not be evaluated during the project period due to lack of research budget.

Figure 14 shows a photograph of the IC device for the Cool Interconnect functional evaluation test to investigate the signal transmission operation of the super-parallel bus interface circuit based on the Cool Interconnect specification. The TSVs and bumps for stacking interconnects were formed in the 2.16 mm square area in the center. The TSVs and bumps for GND and power sources: Vdd (2.5 V) and Vio (3.3 V) were formed around the four sides. The prototyping of the test IC device was done using the shuttle service of a 0.25 μm node CMOS foundry. Figure 15 shows the microphotograph observing the cross-sectional structure after face-to-face stacking by thermo- compression method using the test IC device on which the cone-shaped bumps (no TSV) were formed. Figure 16 shows the test IC device after stacking placed on the evaluation board. Figure 17 is the result of the evaluation experiment for the super-parallel bus interface transmission function incorporated in the device. It shows the power consumption in the interface circuits when the clock frequency was varied in the range of 2-50 MHz. Large signal transmission performance of 51.2 Gbps (1024 bit • 50 MHz) was demonstrated under a low power consumption condition of 87 mW.[36][37] For the interface circuit composed of a 0.25 μm node CMOS device that operates at power voltage of 2.5 V, large capacity transmission was achieved at sufficiently low power consumption. Further power saving can be expected by using a finer node CMOS device.

Based on the electrothermal IC design flow explained in Fig. 10, Fig. 18 shows the thermal analysis result of the temperature increase profile for the central part in the single Si chip placed on the ideal heat sink for the super-parallel bus interface communication interface circuit at 500 MHz operation (high clock frequency was set to emphasize heat generation).[19] The heat dissipation by heat sink is effective and the temperature increase is small. In the practical simulation analysis comparing the actual temperature measurement, the investigation for the thermal properties for the heat dissipation path will become important.

For the operability verification experiment after stacking using evaluation TEG including TSV, the prototype verification could not be done due to lack of development resources and development period, and the verification

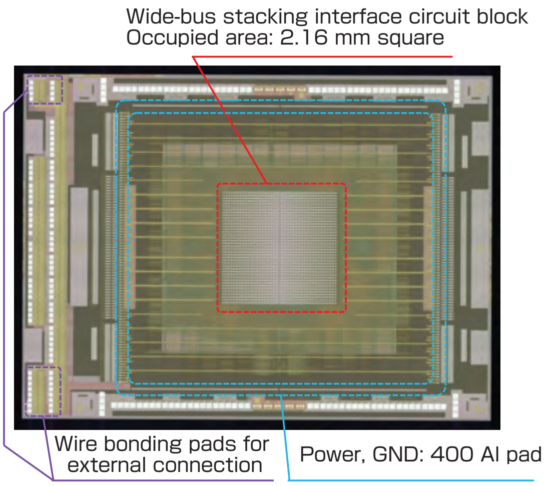

Fig. 14 Test IC device for Cool Interconnect evaluation

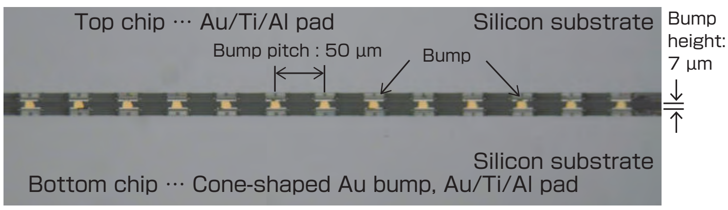

Fig. 15 Cross sectional microphotograph of bump connection structures after stacking by thermo-compression method

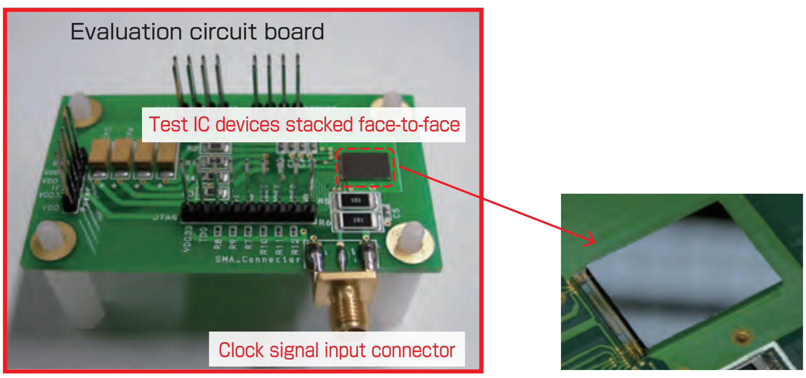

Fig. 16 Test IC device mounted on the evaluation circuit board after stacking

using more practical prototypes in the future R&D project is awaited.

5 Future prospect for the research results

The practical development of the 3D IC chip technology entered a new phase with the start of the NEDO project with its research base at AIST. Specifically, the NEDO Smart Device R&D Project[38] including the 3D various IC stacking technology that aims for real-time high-speed image processing by stacking the sensor device and signal processing device started in FY 2013, and the R&D is currently in progress. This R&D project includes the research plan for designing and prototyping the practical level CMOS-IC device at wafer level, with the participation of a design team of the manufacturer of the application system. At the same time, by the end of the project, we aim to become an open R&D center for 3D IC chip stacking prototyping in Japan by organizing the prototype production process line in AIST, where the 3D IC chip stacking process can be done at wafer level through the participation of the manufacturing device companies. The stacking process will be conducted at chip level for now, but the stacking process at wafer level will be studied concurrently with problem abstraction.

Lastly, the history of the verification R&D is summarized in Table 1.

Table 1. History of the verification R&D

	Development history
2007	Consideration about combination of heterogeneous multi-core architecture and 3D IC chip stacking
2008	Basic research for stacked interface standard (Support Grant for Small and Medium Enterprise, METI)
2009-12	Verification research for stacked interface circuit (Innovative Energy Saving Project, NEDO)
2013-18	Currently engaging in practical development of 3D IC chip stacking technology (Next-Generation Smart Device Development Project, NEDO)

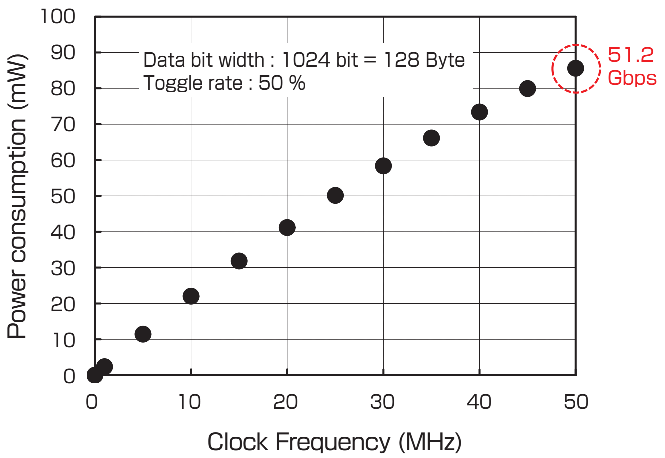

Fig. 17 Dependency of the power consumption on clock frequency in the parallel bus interface circuit

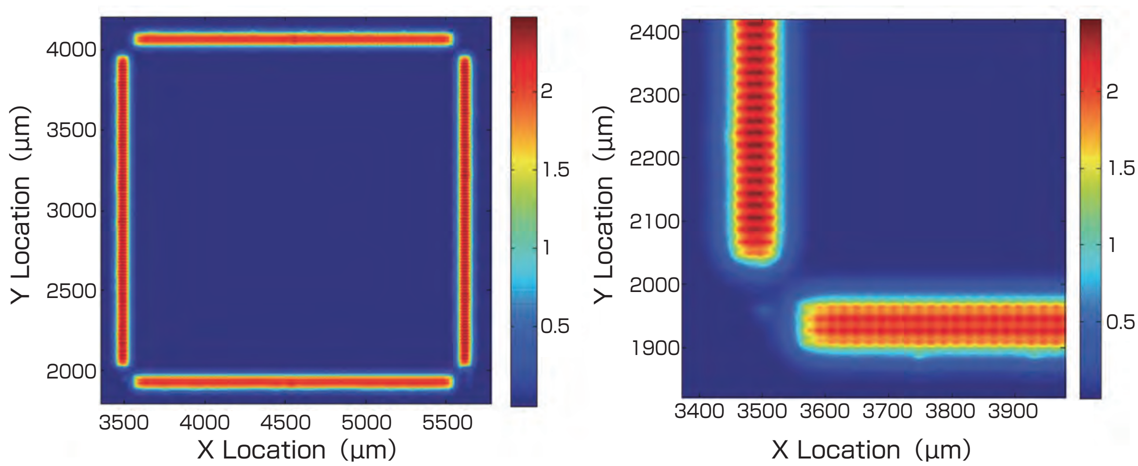

Fig. 18 Result of the simulation analysis for temperature profile in stacked interface circuits during 500 MHz operation

6 Future issues

It is necessary to pour enormous amount of human and research resources to construct the R&D environment for design, prototyping, and evaluation for a practical system that is the final outcome of this research. In order to integrate the fundamental technologies for which the R&D has been conducted and to advance further, we must spend effort to obtain considerable scale of research resources.

Various next-generation low power consumption device technologies are being developed. By combining such technologies and the 3D IC chip stacking technology, an innovative high-performance low power consumption system can be expected. Therefore, it is necessary to accelerate the development of innovative and high-performance circuit and system technologies that maximize the merit of 3D IC chip stacking, through cooperation of researchers and engineers in electronic circuit and system technology fields, and by utilizing the environment for design, prototyping, and evaluation of the 3D IC chip stacking system that matches the practical system. In the near future, we hope that the 3D IC chip stacking prototyping facility that will be constructed at AIST will be utilized effectively as the open innovation hub of industry-academia-government collaboration.

Terminologies

Term 1. System in package (SIP): The method for integrating multiple integrated circuit (IC) chips possessing functional operation into one package; by this method, we can build an IC system. In many configurations, various control circuit chips and memory chips are stacked around the central microprocessor chip on the package substrate.

Term 2. System on chip (SOC): The method for integrating multiple circuit blocks possessing functional operation onto one IC chip; by this method, we can build an IC system. In many chip configurations, various control circuits and memory circuits are integrated around the microprocessor core. Since ordinary IC chips are supplied according to each function, it is necessary to realize packaging and interconnecting for multiple chips on a package circuit substrate. However, in SOC, the system functions that are divided over several chips can be integrated in a single chip and supplied as a single chip.

Term 3. Through-silicon-via (TSV): The electrode that penetrates the substrate of a silicon IC chip in a vertical direction. It is used in the 3D IC chip stacking technology where multiple IC chips are stacked and integrated at high density.

Term 4. Central processing unit (CPU): The integrated circuit that functions as the major information processing device in a computer. It can execute various arithmetic logic processing, information processing, device control, etc. according to the program.

Term 5. Intellectual property (core) [IP (core)]: Partial circuit information to configure a part of an IC device, particularly the one bundled as a functional block. It may be simply called IP.

Term 6. Silicon photonics: The technology where fine optical waveguide structures are created on a silicon substrate that is widely used as an IC device, and the devices with various functions are integrated onto one small chip. Since this enables the integration combining IC devices and optical devices, it is gaining attention as a technology that may enable super-downsizing and power saving of the electronic system.

Term 7. Minimal fab: The innovative semiconductor manufacturing system proposed by AIST using a 0.5-inch wafer as the manufacturing substrate unit. The three features are as follow: (1) 0.5-inch diameter wafer, (2) manufacturing equipment size of 30-cm width, and (3) no clean room through a localized clean production system.

Term 8. Test element group (TEG): The IC chip for evaluation that is specially designed and manufactured to extract various design parameters, prior to the design and manufacture of the actual integrated circuit.

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Discussions with Reviewers

1 Positioning of this paper

Comment (Naoto Kobayashi, Center for Research Strategy, Waseda University)

This paper describes the scenario for the development of 3D IC chip stacking technology, explains the fundamental technologies to realize the goals of the scenario, as well as discusses the integrated design technology and the results. I think the paper is appropriate for *Synthesiology*. However, the most important research goal, its characteristic, and the details of the intermediate integrating technology that combines the fundamental technologies are still unclear. Therefore, I think you should elaborate on those points, and add some descriptions and diagrams that overview the whole research.

Answer (Masahiro Aoyagi)

I think we have not reached the research phase where we can clearly describe the "intermediate integrating technology that combines the fundamental technologies." If we are given an opportunity to write a follow-up report, we will be delighted to take on the interdisciplinary challenge of presenting the example of research method for combining the different technical fields.

Comment (Seigo Kanemaru, AIST)

This paper reports the R&D results at AIST on the 3D stacking technology that is a new method to increase the integration level of the integrated circuit. Although the 3D stacking technology has existed as an idea before, it did not become a main topic of R&D due to the technological difficulty of achieving three dimensional integration, and the integration level of IC was improved through the size reduction of the transistors. Currently, as we recognize the limitation of size reduction, the 3D stacking technology is coming into light again. However, this technology has many issues, and the fundamental technologies must be developed to solve them. I think AIST has taken the strategy to utilize the limited research resource efficiently to work around these issues. I believe if you clearly discuss your efforts from these perspectives in this paper, it will be useful information for those engaging in other research issues where the integration of fundamental technologies is involved.

Answer (Masahiro Aoyagi)

I added the descriptions of the specific strategic efforts for effectively utilizing the limited research resource to tackle the issues of 3D stacking technology, and the priority of issues and the obtainment of research resources, in an understandable, chronological order.

2 Goals

Comment (Naoto Kobayashi)

I can see that you are aiming for systematic development of the 3D IC chip stacking technology in this paper. However, I hope you state what and how much you aspire to realize as practical technology unseen anywhere else, and how the companies can use such new technology. Particularly, you write in Chapter 6, "the final outcome is to provide an R&D environment for design, prototyping, and evaluation that matches the practical system," but if you are setting that as your final goal, I think you should describe what is the realistic output you set as your goal of this research. I think you should state this at the end of Chapter 2, but in that case, I think you should make the title of Chapter 2, for example, "Advancement of the electronic hardware system integration technology by 3D IC chip stacking and the aim of this research."

Answer (Masahiro Aoyagi)

About your indication, "I think you should describe what is the realistic output you set as your goal of this research," I added some descriptions to the end of Chapter 2.

3 Comparison with competing technologies

Question & comment (Seigo Kanemaru)

Please describe in understandable terms, the advantages and disadvantages of the SOC, SIP and 3D stacking technologies that you show in Fig. 1, from the viewpoints of constructing a competitive electronic system. If you can clarify the reasons for the high expectations for the 3D stacking technology that is technologically difficult, I think the readers can more readily understand the value of this paper.

Answer (Masahiro Aoyagi)

Considering the performance, power consumption, size, design cost, manufacturing cost, and others as the indices of increased performance, the 3D stacking technology can be achieved in various combinations (depending on priority given to performance, cost, etc.), and I think it is difficult to compare simple advantages and disadvantages. In this paper, we describe the representative example giving priority to power consumption.

4 Specific fields of application for the 3D stacking technology

Question & comment (Naoto Kobayashi)

Large investment is necessary for the development of general-purpose semiconductor technology, and the technology faces severe competition and the pace of change is fast. You write (in Chapter 2) that the SOC technology is facing difficulties in business for such reasons. If the 3D stacking technology is useful, such high-end technology will be put to practical use in the near future, and similar business issues may arise. On the other hand, I think the functional semiconductor devices that combine sensor, actuator, and others require very special technology, and the TSV is already used in some parts. What is the final form (specific field of application) of the 3D stacking semiconductor that you are aiming for in this research?

Answer (Masahiro Aoyagi)

I added the description in Chapter 5 on the final form (specific field of application) of the 3D stacking semiconductor that we are aiming for in this research.

5 Cost reduction by the 3D stacking technology

Question & comment (Naoto Kobayashi)

The 3D stacking technology is gaining attention around the world, and is already incorporated in stacking SOC and DRAM, but I hear that, in reality, the cost is one of the bottlenecks. In the text (Chapter 2), you write that the cost of development and manufacturing can be reduced greatly by 3D IC chip stacking technology compared to SOC. Please tell us if you have any specific cost estimates or projections for the 3D stacking technology as an advanced SIP technology.

Answer (Masahiro Aoyagi)

For a cost estimate, an accurate one is difficult within the range of information that can be disclosed. I added some general description, and added some source material from a technological survey company in the reference section.

Securing a stable supply of critical raw metals

— Efforts and issues for the securement of rare-earth resources —

Tetsuichi TAKAGI

[Translation from *Synthesiology*, Vol.9, No.1, p.15-25 (2016)]

In the early 21st century, metal prices soared due to the economic development of newly industrialized countries. Moreover, a rare-earth resource crisis occurred between 2009 and 2012 due to export restrictions imposed by China. Against this background, AIST set up a research base for critical metal resources, and established collaborative relationships with some foreign geological survey agencies (GS) from 2010. Furthermore, joint surveys were conducted with GS of South Africa, United States, Brazil, Mongolia, and others. While undertaking these surveys, we found a promising prospect for heavy rare-earth in South Africa. After the autumn of 2011, however, the prices of rare-earths collapsed, and the majority of rare-earth exploration/mining programs worldwide were put on hold. This sequence of events revealed the risks that accompany the development of critical metal resources. To mitigate the impact of future crises, AIST should continue research and development of rare-earth resources.

Keywords : Rare metal, mineral resource, rare-earths, stable supply, BRICS

1 Introduction

1.1 What are rare metals?

The metal resources are categorized into: common metals that are produced and consumed in large quantities such as iron and aluminum; base metals that are the basic materials of the industry; precious metals such as gold and silver; and rare metals that have low production volume and usage but are important in industry (Fig. 1). In Japan, the Ministry of Economy, Trade and Industry (METI) has designated 31 species of metals as rare metals. They are distinguished from other metal resources and policies are taken to ensure their stable supply.[1] The rare earth elements are handled as a kind of metal among the rare metals, but in practice, rare earth is a general term for 17 metals including 15 lanthanide elements plus Scandium (Sc) and Yttrium (Y). The lanthanide elements with atomic weight lighter than Europium (Eu) are called light rare earth elements, while those that are heavier are called heavy rare elements. The light rare earths are used in fluorescent materials, glass abrasive, oxygen scavengers for iron and steel, Ni-H batteries, oil refinement catalysts, and others. The heavy rare earths are mainly used in high-performance magnets.

1.2 Rare metal shock

The Japanese metal mining industry gradually contracted after the World War II due to the decrease and depletion of ore reserves. However, it declined rapidly since the 1980s due to increased yen value, increased cost of labor, pollution problems, and others. The major large-scale, high-

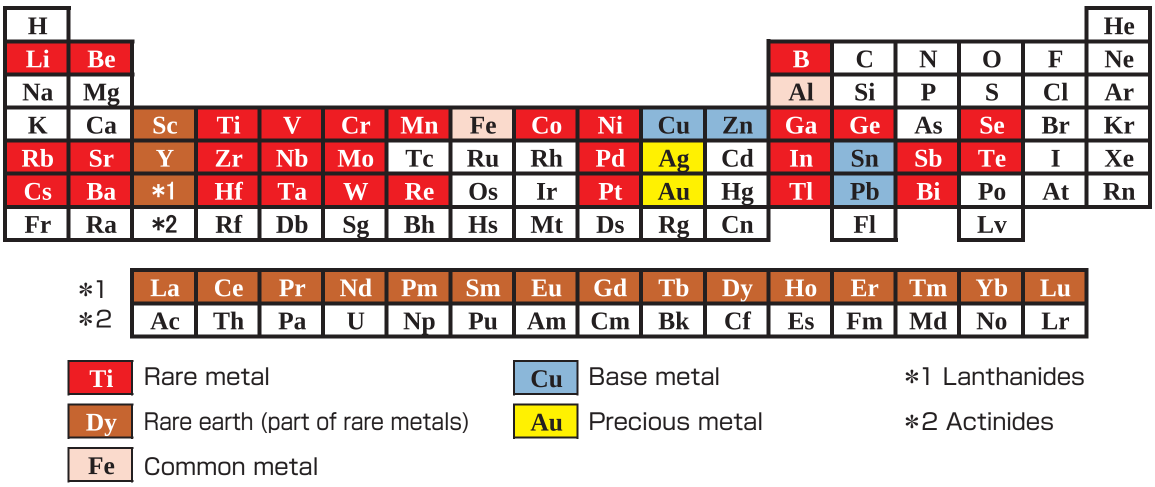

Fig. 1 General categorization of the metal resources

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grade mines terminated their activities (Kuroko mines of Hokuroku Region, Akita Pref. in 1993; Kamioka Mine, Gifu Pref. in 2001; and Toyoha Mine, Hokkaido in 2006), and the only mines still in operation are some gold mines (such as Hishikari Mine, Kagoshima Pref.). Today, the Japanese industries are dependent totally on imported metal resources, and maintaining stable supply is a vital issue. Fortunately, from the 1980s to the beginning of 2000s, the prices of metal resources were relatively stable, and they could be imported liberally by Japan's economic strength. During this time, a sense of crisis toward the procurement of metal resources was not necessarily high for both the Government and private companies.

The prices of nonferrous metal resources that used to be stable rose rapidly from about 2004. This was the start of the "rare metal shock" (Figs. 2 and 3). It was caused mainly because the increasing consumption of metal resources by the emerging industrial countries such as BRICS surpassed the buffer capacity of the market. The price increase stopped temporarily after the Lehman Shock, but it started to rise again and continues to the present. The competition for nonferrous metal resources such as rare metals and base metals has become global, and it has passed beyond the capacity of private companies and has become an international matter. The procurement of mineral resources now requires the combined forces of politics, diplomacy, and

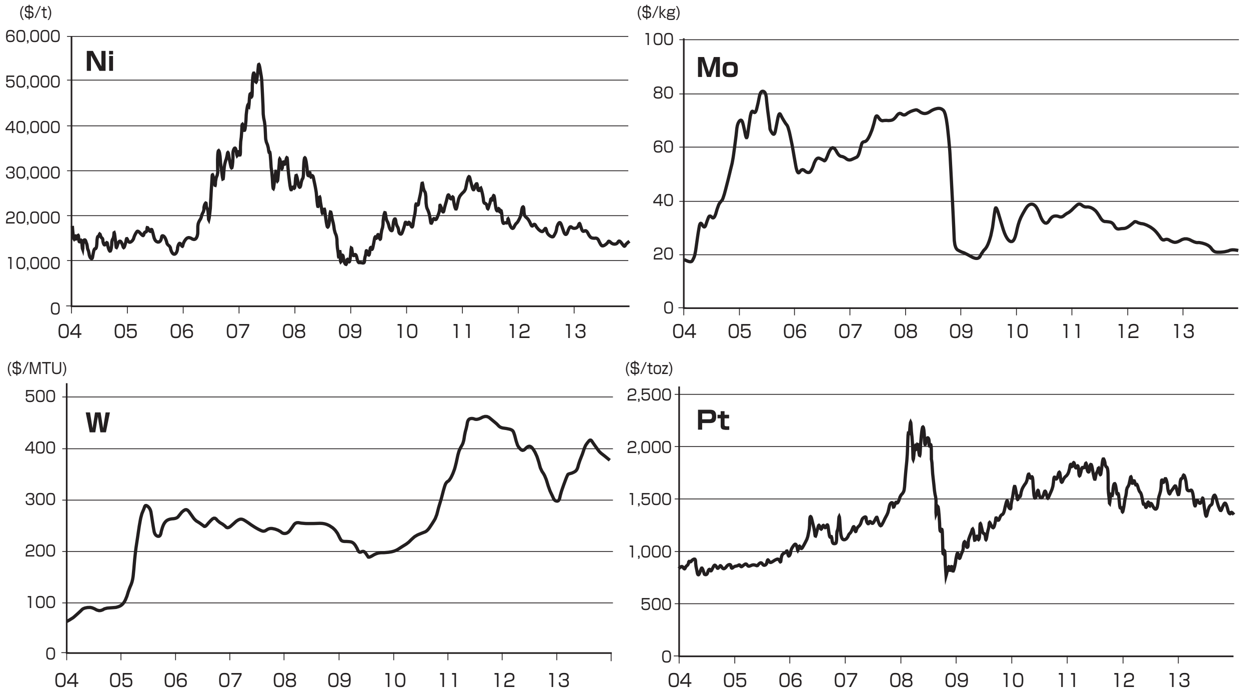

Fig. 2 Transition of the prices of major rare metals (compiled by METI based on the prices of the London Metal Exchange)

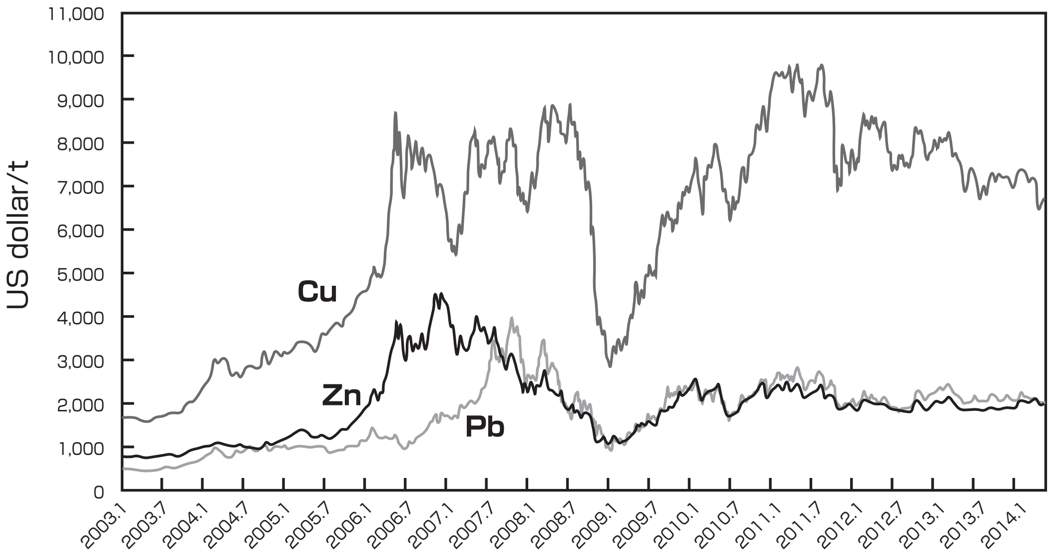

Fig. 3 Transition of the prices of base metals (copper, lead, and zinc) (London Metal Exchange)

science and technology, not just economic power. METI set up the "Rare Metal Procurement Strategy"[2] in July 2009, and the Government came to the forefront to take active measures for resource procurement strategies.

2 Objective of the rare metal resource research

2.1 Rare metal resource research

The research of rare metals can be roughly divided into materials science and earth science. In the former, the objective is the R&D for high-performance materials using rare metals, reduction of rare metal use, alternative materials, and recycling. In the latter, the objective is the exploration of rare metal resource and resource evaluation (the development of mineral processing and refining technologies partly spans across both fields). Since AIST engages in general research of rare metals, a rare metal task force was set up in 2006, and research was conducted on materials science and earth science like two wheels of a car.[3] In this paper, the earth science research of rare metals will be addressed as the "rare metal resource research."

2.2 Characteristic of rare metal resources

Mineral resource development generally requires about 10 to 15 years from exploration to commercial mining. Since large cost is necessary for various surveys and tests, the project cannot be continued unless there is certainty of profit for the exploitation. There are many cases where the development plans were stopped due to the issues of insufficient minable reserves or low grade, as well as due to problems of costs needed for mining, processing, and refining. The international market is well established for nonferrous metals such as base metals and precious metals, and stable profits can be gained. Also, refineries are in operation in Japan for copper and zinc, and the sales volume is stable since there is a need to continuously supply the ore to the furnace. Therefore, the major mining companies and general trading corporations carry the burden of development risks, and engage in active investment and development. On the other hand, although essential in advanced industries, only small amount of rare metals is mined and used, and the profits by sales and purchases are small. Also, the species of required rare metals may change in a short period of time due to the advances in technology. There is no international market established for most rare metals, and the prices shift greatly due to political and economic reasons including speculation, war, mine strikes, or protectionism. Due to high risks, the resource development of rare metals is often done by venture companies or junior mining companies (companies that specialize in exploration with no large-scale capital such as mines). Many rare metal deposits are "nonconventional types" where the occurrence is totally different from the base metal deposits, and advanced geological and mineral processing knowledge are required for their development. To procure the rare metal resources with certainty, the resource potential evaluation at the early stage of development must be done by public institutions (such as geological surveys and universities) instead of private companies, to determine the prospective cases to reduce the investment risks as much as possible. Compared with other engineering fields at AIST, rare metal resource research is characterized by the fact that the cycle time of R&D is extremely long, and the risk factors spread widely beyond technological development. Therefore, long-term continuous R&D is necessary.

3 Strategy for rare metal resource procurement

As mentioned before, rare earths are part of rare metals, but in the past recent years, the procurement strategy for rare earth resources in Japan was almost equivalent to the procurement strategy for rare metal resources. Therefore, in this chapter, I shall discuss the strategy taken by AIST for rare earths.

3.1 Rare earth crisis

The rare earths were mainly produced in the placer deposits of India until the 1980s, but when the demand increased in the 1990s, they were produced mainly by the Mountain Pass Mine in the USA. From the end of 1990s to the beginning of 2000s, the production volume from China increased rapidly, and China dominated over 90 % of the share in the world market through its low price strategy. Not only was the Mountain Pass Mine unable to compete with China in terms of cost, but also the environmental pollution problem by wastewater drainage forced the mine to close in 2002. China gradually started to regulate export by setting the ceiling on rare earths from about 2007, and the supply risk started to become apparent. However, from about 2009 when the effect of Lehman Shock settled, the demand-supply balance was toppled due to the tightening of the export ceiling, and the price soared from the latter half of 2010. Since the Senkaku Island incident in September 2010, when a Chinese fishing boat collided with the Japan Coast Guard ship, the rare earth export from China to Japan was halted, and the "rare earth crisis" occurred as the Japanese industries faced a serious lack of rare earth supply. The rare earths marked the highest price in history on August 2011 (Fig. 4).

3.2 Scenario for rare earth resource development

Rare earth resource development starts with the discovery of mineral prospects (outcrop where the concentration of ore minerals can be found on the ground surface) as in base metals and precious metals. A mineral prospect is studied by specialists to clarify its occurrence and extent by ground surface survey, and confirmation is made on whether it is an ore deposit (place where the mineral is concentrated at a certain amount). In the following reconnaissance survey, the extent of hydrothermally altered zone and the hydrothermal origin are studied if it is a hydrothermal deposit, or the distribution and thickness of the horizon in which the heavy minerals are concentrated are studied if it is a placer deposit. This allows the evaluation of the size and reserve of the ore. In the case of rare earth resources, an initial mineral processing test is likely to be done at this stage. This is because unless the ore containing rare earths can be readily separated and extracted, development will be difficult even if the rare earth content (grade) is high. In many cases, a company or geological survey may execute the survey up to this stage.

If it is determined that the deposit is promising, close investigation follows. This includes drilling surveys and geophysical exploration that are conducted to determine the amount of reserve. Moreover, highly dense drilling (several tens to several thousands of holes) and test mining are done to estimate the minable reserve. The drillings and geophysical exploration are expensive, and therefore, in Japan, when the interests of the Japanese companies are involved, the normal practice is for the Japan Oil, Gas and Metals National Corporation (JOGMEC) to conduct such surveys solely or jointly with private companies, and then hand the project over completely to the companies at an appropriate stage. When the main developing companies are determined and the specific development plans for the mine are drawn, the environmental impact assessment and infrastructure development are done. Only after all these phases are cleared, the mine is opened. In the case of rare metal resources including rare earths, the development risk is greater than other nonferrous metals, and in many cases, support by JOGMEC or the Japan Bank for International Cooperation (JBIC) may be necessary after the mine starts operation.

3.3 Requirements for rare earth resource development

Currently, because China dominates most of the rare earth resource supply, we must develop or redevelop rare earth deposits outside China to ensure supply of new raw materials. The requirements include the following items.

Grade: To be competitive against the Chinese rare earth ore, ore that contains abundant light rare earths must have 4 % or more of total rare earth quantity (in terms of oxide), and ore that contains heavy rare earths must have 1 % or more.

Rare earths containing minerals: Readily soluble carbonates (bastnäsite, etc.) or phosphates (monazite, xenotime, etc.) are desirable. Refractory minerals (phosphates containing aluminum, niobium minerals, zircon, etc.) are expensive to dissolve. Also, processing is difficult unless the average grain size is 100 μm or more.

Reserve: Several tens of thousands of tonnes or more for total rare earths.

Mining method: In principle, it should be open-pit mining.

Radioactive material: High concentration of thorium is often found in monazite. In the case where there is high volume of waste materials containing thorium, these must be stored or disposed by burial according to the standards[4] of the International Atomic Energy Agency (IAEA). Although there is no definite threshold, less than 1,000 ppm for unprocessed ore (raw ore) is desirable.

Social environment: Infrastructures such as roads and railways must be available. There must be sound security enforcement and mining laws.

In the case where AIST conducts the exploration of rare earth deposits, whether the target mineral occurrence fulfills the above requirements will be checked through various surveys and analyses. Therefore, it is important to request information to the geological surveys of the respective countries beforehand, and carefully plan the survey strategy.

4 Effort on the rare earth resource research

In this chapter, response to the aforementioned rare earth crisis will be described as an example in which AIST contributed to the Government’s rare metal resource

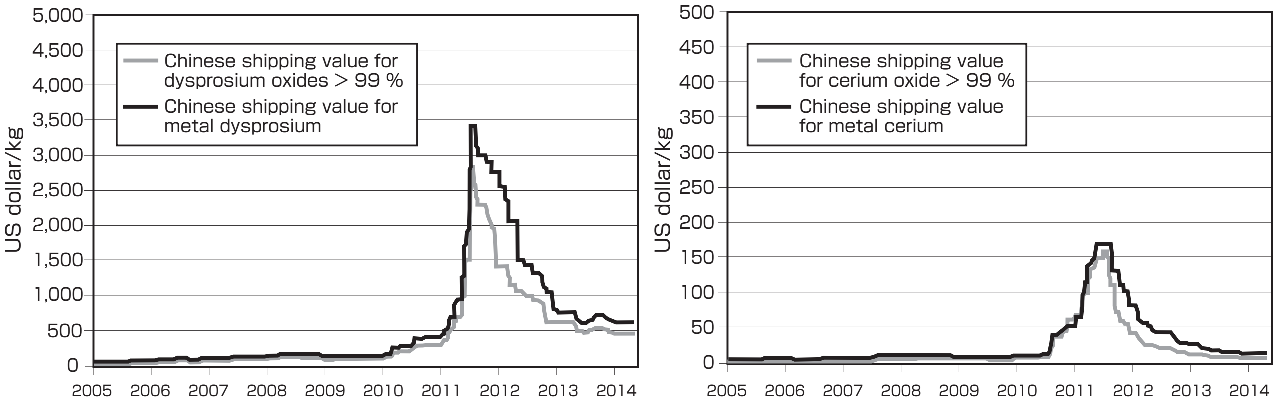

Fig. 4 Transition of the prices of dysprosium (heavy rare earth) and cerium (light rare earth) (compiled from the material in Metal Pages Website)

procurement strategy.

4.1 Establishment of the research base for rare metal and rare earth resources

With the occurrence of the rare earth crisis, the Japanese Government set aside a budget for measures to procure rare earth resources in the supplementary budget for fiscal years 2010 and 2011, and provided large funds to AIST for a subcontract project of the Agency of Natural Resources and Energy (actual execution of the fund was for FY 2011 and 2012). Prior to this, in autumn 2010, the Agency requested AIST to establish a research base for rare metal and rare earth resources. However, the mineral resource research at AIST had been shrinking since the days of the former Agency of Industrial Science and Technology, and the Institute for Environmental Management Technology (part of the former National Institute for Resources and Environment) that was in charge of the development of mineral processing and refining technologies had shifted completely to recycling technology research. Even at the Institute for Geo-Resources and Environment (GREEN), which engages in ore genesis research and exploration technology development, there was only one research group, reduced from the four sections at the old Geological Survey of Japan. The organization was too weak to form a research base. Therefore, the GREEN would conduct the rare earth deposit exploration and initial processing tests, while the Tohoku University would be in charge of the full development of the mineral processing and metallurgical technologies, and the aforementioned supplementary budget was used to start a new base. The Strategic Urban Mining Research Base (SURE) was established in the Institute for Environmental Management Technology in 2014, and has become the center of recycling R&D for rare metals.[5]

The GREEN introduced the facilities for ore and mineral analyses and mineral processing tests during the two years from 2011 to 2012 to organize the research base.[6] The facility for analyzing minerals and rocks was available at the GREEN, however, metal ore has extreme concentration of certain elements compared to ordinary rocks, and the rare earth ore tended to have high concentration of radioactive elements such as thorium. Therefore, to conduct full rare metal and rare earth resource research, it was necessary to construct a new experimental facility separate from the old facilities, to avoid contamination and to properly dispose the wastewater and dust generated in the experiment. One of the newly introduced devices that should be particularly mentioned is the laser ablation inductively coupled plasma mass spectrometer (LA-ICPMS).[7] The LA-ICPMS is a device that concentrates and irradiates laser beams to a solid that is the analysis subject, takes the evaporated surface materials into the ICPMS as aerosol along with high-pure argon gas, and conducts the chemical analysis (Fig. 5). The process does not require pretreatment of the sample, and allows local analysis at high precision. In the analysis of rare earth ore using this device, there is no problem of undissolved samples that could not be avoided in the conventional acid dissolution method, and the analysis can be done quickly in two minutes per sample.[8] The device at GREEN was improved and new functions were added for ore analysis. It has been used for analysis of several hundred pieces of ore from a dozen countries, and contributed greatly to rare metal resource research. The next device that should be mentioned is the mineral liberation analyzer (MLA) (Fig. 6). The MLA is a device that combines a regular scanning electron microscope and powerful image analysis software, and it has the function of calculating and displaying statistical data such as mineral ratio, grain size, and composite ratio of the ore or mineral powder from a single sample in a few hours. This device was also used to analyze several tens of rare metal ore samples, and greatly contributed to the formulation of the evaluation and processing methods. Also, sensitive high-resolution ion microprobe (SHRIMP) (Fig. 7) and high-voltage pulse selective crushing equipment (manufactured by SELFRAG AG) have been introduced and the results are being produced. As mentioned earlier, the mineral processing lab is equipped with wastewater and dust disposal facilities.

Fig. 5 Laser ablation inductively coupled plasma mass spectrometer (LA-ICPMS). Laser light source by Cyber Laser Inc., ICPMS by Agilent Technologies Japan, Ltd., and other parts were assembled in house.

Fig. 6 Mineral liberation analyzer (MLA) by FEI

For wastewater, by a process using the vacuum distillation volume reduction device, the suspension water containing heavy metals and radioactive materials is prevented from escaping outside the lab.

4.2 Building research cooperation framework with overseas geological surveys

In the measures against rare earth crisis, the building of research cooperation framework with overseas geological surveys is essential in terms of organizing the research promotion environment. The following three can be given as the reasons why this is very important.

1) Collection of highly reliable resource information of the resource-producing countries: When conducting overseas resource survey, it is necessary to narrow down the prospective areas by obtaining preliminary information from official geological survey of the country.
2) Ensuring safety during overseas survey: Cooperation of the official geological survey is necessary to safely conduct survey in accordance to the local security and natural environment.
3) Contribution to resource diplomacy: By showing that we are cooperating with the resource-producing countries to others, we can appeal that Japan is strategically working on the measures to procure resources. By doing so, this may prevent other resource-producing countries from taking extreme resource policies such as banning export of rare earths to Japan.

The partners of international research cooperation are assumed to be countries with high potential of prospective rare earth deposits. However, selection is based on the comprehensive examination based on the METI policy, request of local government organizations, past record of cooperation, security and political situation, and others. The history of major international research cooperation will be presented below.

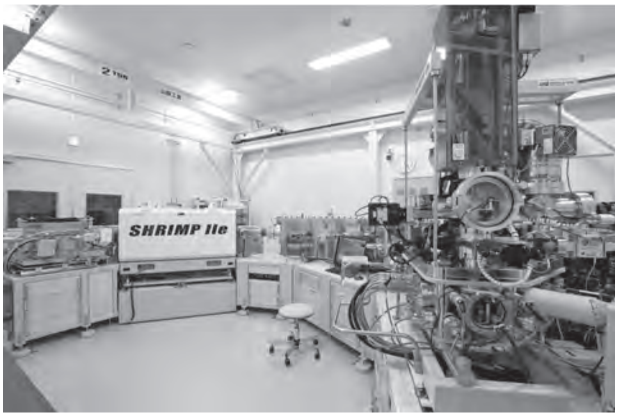

Fig. 7 Sensitive high-resolution ion micro probe (SHRIMP) by Australian Scientific Instruments

USA: Since the occurrence of the rare earth crisis, the Japanese Government became active in the attempt to solve the problem, with focus on the Japan-USA cooperation. In November 2010, the Japan-US Rare Earth Roundtable was held at the Lawrence Livermore National Laboratory, and opinions were exchanged by the rare earth researchers of Japan and the US. AIST (researchers of resource saving, recycling, and resource exploration) participated in this roundtable along with the specialists of METI, JOGMEC, New Energy and Industrial Technology Development Organization (NEDO), and major universities. In January 2011, the Japan-US Rare Earth Conference was held at the US Department of Energy. The personnel in charge from various ministries and agencies of Japan and JOGMEC attended this conference, while from AIST, only the author attended due to a policy decision of giving priority to cooperation in the resource exploration field, and future Japan-US research cooperation was discussed. At this conference, the research cooperation on rare metal resource was agreed between AIST and the US Geological Survey (USGS). After nonofficial meetings, a memorandum of research cooperation was formally signed between AIST and USGS in San Francisco in December 2011. On-site surveys of rare earth mineral occurrences were done in the southern part of Alaska in August 2011, eastern Missouri in November 2012, southern California and central Georgia in October 2014, and on-site surveys were also planned for FY 2015.

Republic of South Africa: South Africa is a mining giant that produces abundant rare metals such as the platinum metal groups and chromium. A memorandum for research cooperation was signed by three parties, Council for Geoscience (CGS) of South Africa, JOGMEC, and AIST in 2007, before the rare earth crisis. Ever since, survey research (will be explained later) has been done actively. In the agreement at the Japan-South Africa Conference of Ministers of Mining held in 2013, the promotion of this research cooperation was stated clearly. In March 2014, the research cooperation memorandum between AIST and CGS was updated, and continues to be in effect today.

Mongolia: Since the times of the Agency of Industrial Science and Technology, there is a long history of research cooperation with Mongolia in the mineral resource field, through the projects of the International Transfer of Industrial Technology (ITIT) and the Japan International Cooperation Agency (JICA), and exchange at researcher level has continued after the establishment of AIST. In October 2010, faced with the rare earth crisis, a research cooperation memorandum was formally signed by three parties, AIST, JOGMEC, and the Mineral Resources Authority of Mongolia (MRAM). On-site survey of the rare earth mineral occurrences was conducted in the southern Gobi region in 2010, and with the cooperation of private companies of Mongolia, surveys were done in the western region of

Mongolia in 2011~2012. Currently, the mining districts are being reviewed due to the changes in mining laws of Mongolia, and the research is temporarily suspended until the rare metal resource policy of Mongolia is settled.

Federative Republic of Brazil: In the joint seminar of AIST, Companhia de Pesquisa de Recursos Minerais (CPRM), and Departamento Nacional de Produção Mineral (DNPM) held at the CPRM headquarters in November 2009, the research cooperation was agreed in several earth science fields including the rare earth resource research. Later, after Japan-Brazil Joint Committee Meeting on Cooperation in Science and Technology in December 2010 and other informal meetings, a research cooperation memorandum was officially signed between AIST and DNPM in December 2012. The author presented a lecture on the Japanese rare earth resource policy at the hearing of the Federal Senate, National Congress of Brazil in June 2013. On-site surveys of the rare earth mineral occurrences were conducted in the southern part of the State of Goiás and central southern area of the State of Minas Gerais in 2013, and in northern Goiás in February 2014.

Other countries: The organizations with which research cooperation memorandums were signed for rare metal and rare earth resources include: the Department of Geological Survey and Mineral Exploration (DGSE), Myanmar; Korea Institute of Geoscience and Mineral Resources (KIGAM); and Department of Mineral Resources (DMR), Thailand. Regular human resource exchange is done with these institutions. Although research cooperation memorandums have not been signed, we have research exchange with: Geologian tutkimuskeskus (GTK) of Finland; Maden Tetkik ve Arama Genel Müdürlüğü (MTA: General Directorate of the Mineral Research and Exploration), Turkey; Geoscience Australia; and several other institutions.

4.3 Survey of rare earth mineral deposits and occurrences – The case of South Africa

In this subchapter, I describe the history and the future prospect in South Africa where the survey research has reached the advanced stage.

Discovery of mineral occurrences: In the northeastern region of South Africa including the capital city Pretoria, there is a giant exposure of Bushveld Complex that spans 460 km east-west and 250 km south-north. This rock body is composed of rocks that were formed as the magma cooled and solidified deep underground two billion years ago, and the platinum group elements and chromium that are the main rare metal resources of South Africa are produced from the deposits of the Bushveld Complex. There are several fluorite (CaF_2) deposits distributed in this rock body region, and some are actively mined as the raw material for fluoride. It is known worldwide that the fluorite deposits are often accompanied by high concentration of rare earths, and the mineral occurrences of rare earths were confirmed in the reconnaissance survey before 2008 at the fluorite mines that were in operation in the area. However, most of the operating mines were managed by foreign companies operated by white people, and the survey research under South Africa's Black Economic Empowerment (BEE) policy was difficult. In the on-site survey conducted jointly by AIST and CGS in September 2009, a rare earth prospective area was found near the old fluorite mine in the central area of the Bushveld Complex. This occurrence was in an undeveloped region, but the CGS researchers had detected the alteration zone in the ground surface accompanying the exploration of the fluorite deposit. As a result of analysis conducted at AIST, it was confirmed that this prospect could be a promising deposit abundant with heavy rare earths.

Application for the mine exploration district: During 2009 to 2010, the rare earth prices were soaring, and it was necessary to protect this rare earth deposit from other exploration companies. Therefore, CGS applied for the mine exploration district to the Ministry of Mineral Resources through the African Exploration, Mining and Finance Corporation (AEMFC). Since the deposit region was state-owned land and all land managers were native people, it was possible to conduct on-site survey without trouble.

Execution of exploratory drilling: From the result of the radioactive exploration conducted by CGS, the extent of the deposit was narrowed down, and five shallow exploratory drilling was done in FY 2012, and three in FY 2013 (Fig. 8). As

Fig. 8 Shallow exploratory drilling conducted in South Africa (August 2013)

a result, it became clear that the rare earth grade was relatively high in the lateritic weathered crust dozens of meters from ground surface, and similar grade was found in the pegmatitic zone in the concealed unweathered plutonic rock. The average rare earth grade is around 1 % in terms of oxide, and has the characteristic of containing abundant yttrium and heavy rare earths. The rare earth containing minerals are phosphates that are relatively easy to dissolve, and the thorium content is less than 100 ppm, that is slightly higher than ordinary rocks. Therefore, it was determined that development would be possible from the weathered crust that was easy to mine.

Mineral processing test: For the development of this deposit, the essential condition is to establish the technologies to extract the rare earth containing minerals in the weathered crust and to make concentrates. This is because if the weathered crust rocks are dissolved in acid or alkali, large amount of chemicals will be necessary, and this will not be cost effective. In FY 2013-2014, several tens of kg of samples were brought to AIST from the site, and emphasis was shifted to a lab-scale processing test. In FY 2015, we asked cooperation from Waseda University and Mintek of South Africa, and plan to accelerating the mineral processing test to improve the rare earth quality of the concentrates.

Future prospect: In December 2013, part of the survey results of this rare earth deposit was disclosed at a hearing held in Tokyo, but there was no Japanese company that showed interest at that point. In the future, after obtaining certain results in the mineral processing test, we plan to organize the total results and disclose this information again to the companies and JOGMEC. Also, it is likely that we will add more survey research necessary to increase the materials on which decisions can be made. In any case, there is a limit in continuing the survey research paid by the funds of AIST and CGS alone, and external (JOGMEC, private companies, etc.) funding is necessary to advance the development of this deposit. If it becomes possible to produce heavy rare earths from this deposit, we will have a new supplier other than China. Even if the production volume is small, this will give a sense of security to the market that heavy rare earths can be obtained without the country risk of China, and this is expected to help stabilize the prices.

4.4 Construction of the rare earth resource database

When the government or private companies create a strategy for rare earth resource procurement, it is necessary to understand the distribution, size, properties, and others of the rare earth resources around the world. If it becomes apparent that the deposit of rare earth resources is concentrated in a certain country, it becomes possible to convince that country to export the products at appropriate prices as a responsibility to the international community. Therefore, the USGS annually discloses various mineral resource information such as the Mineral Commodity Summaries on the website.[9] In the case of rare earth resources, worldwide exploration and development have been conducted using the database by Orris and Grauch[10] published in 2002. However, 12 years have passed and with the occurrence of the rare earth crisis, the time has come to totally review the database for rare earth resources and to recreate the strategy for resource procurement. Therefore, AIST is working on the rare earth resource database jointly with USGS, and the first results will be published in 2016.

The material flow analysis and demand-supply projection for rare earths are being conducted concurrently, and results have been obtained.[11][12] The objective of this research is to analyze the flow from import, commercialization in Japanese industry, to export, disposal, or recycling of rare earths, as well as to forecast the shift in supply and demand based on the future prices and technological trends, and to contribute to the strategic planning for resource exploration, resource saving, and recycling.

5 Issues after the rare earth crisis

5.1 Crash of rare earth prices

The prices of rare earths reached the peak in August 2011, and dropped to 1/30 for cerium and 1/4 for dysprosium in 2013 (Fig. 4). This was due to the fact that China released the stock that was built up due to the export ban, and the Japanese companies that used rare earths switched to alternative products and actively reduced the amount of rare earths used. However, due to the crash of rare earth prices, about 100 rare earth resource development programs that were being conducted around the world were almost all delayed, suspended, or terminated, except for the Mountain Pass Mine in USA and the Mt. Weld Mine in Australia. As mentioned earlier, a period of about 10 to 15 years is required for mineral resource development, and it was difficult to develop new mines in a time period of about four years within which the rare earth crisis became apparent and the prices crashed. Also, Molycorp Minerals, the operator of the Mountain Pass Mine that continued operation for a while after the rare earth crisis, applied for “Chapter 11” bankruptcy reorganization on June 2015. This event reminded the mining people how high the risk is for rare metal resource development.

5.2 Role of AIST in full-scale research

Although the rare earth crisis settled down, the diversification of rare earth supply sources did not occur, and the domination by China, just like before the crisis, continues to the present. Rare metals, similarly to rare earths, for which China dominates 80 % as the supplier, includes tungsten, antimony, and others (Fig. 9). Depending on the international situation, China may again play the resource card, and the potential for crisis has not decreased. The rare earth crisis is not a transitory event. It will be too late if measures are taken at the occurrence of the next rare earth crisis. However, as mentioned in Chapter 2, rare metal and rare earth resource development is a high risk for private companies, and there are limits to preliminary preparation and investment. Currently, AIST, in collaboration with other organizations (Agency of Natural Resources and Energy, JOGMEC, overseas geological surveys, universities, etc.), is the only research institution that is capable of continuous and systematic information collection, survey research, and human resource training for rare metal and rare earth resources. The execution of R&D with medium- to long-term vision that is not affected by immediate resource demand, in preparation of the second and third rare earth crises that will certainly occur in the future, is full-scale research that AIST should take on (Fig. 10). As of 2015, the attention toward and the sense of crisis for mineral resource supply has decreased due to the lowered prices of resources arising from the economic deceleration of China. However, lowered resource prices lead to selective mining at high-grade zones that yield profit, which brings about shortened lifespan of the mines and depletion of the reserves. In preparation for the reaction against the lowered resource prices that is sure to happen in the future, AIST has the responsibility to execute full-scale research.

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I am thankful to Yasushi Watanabe (Akita University, former Group Leader, Mineral Resources Research Group) and the people of Mineral Resources Research Group, GREEN who are involved in this research. I am also sincerely grateful to the people of the Mineral Resources Section, Agency of Natural Resources and Energy and the Metal Resources Development Headquarter, JOGMEC.

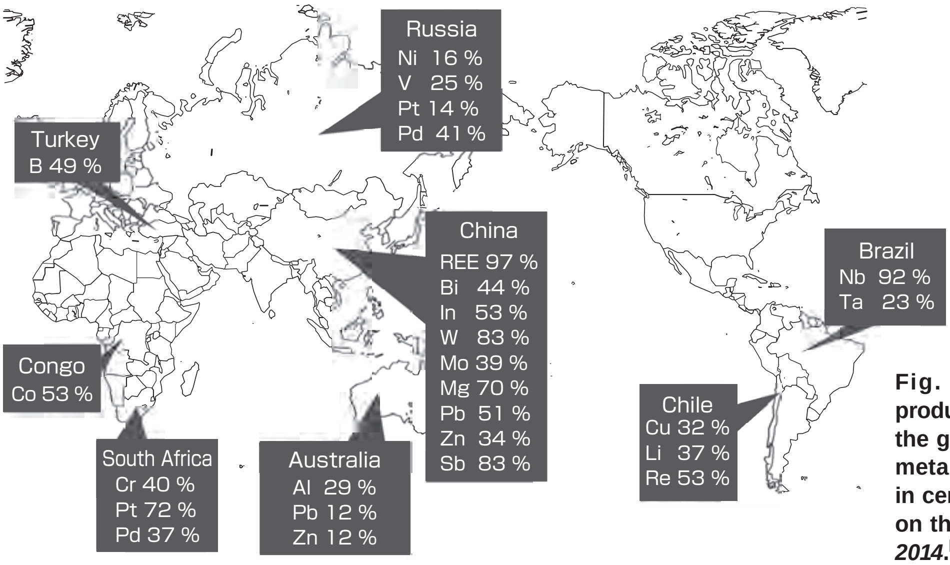

Fig. 9 Percentage of rare metal production volume of each country in the global production. Includes base metals that are highly concentrated in certain countries. Compiled based on the *Natural Resource and Energy 2014*.[13]

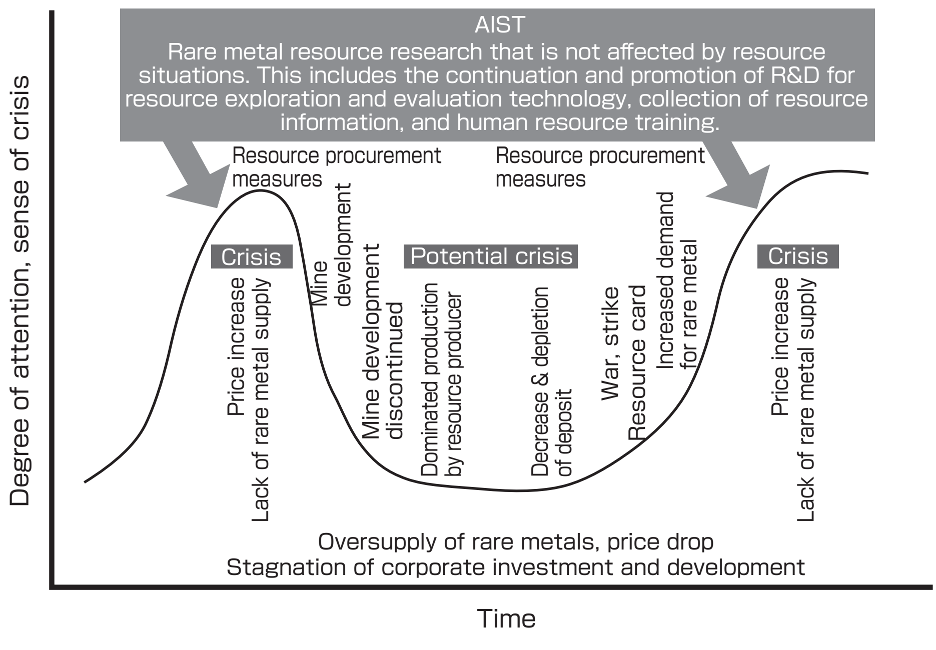

Fig. 10 Conceptual diagram of full-scale research in the rare metal resource research

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Discussions with Reviewers

1 Overall

Comment (Yusaku Yano, Research Planning Division, Geological Survey of Japan, AIST; Keizo Kobayashi, Structural Materials Research Institute, Department of Materials and Chemistry, AIST)

METI placed great expectations on the Mineral Resources Research Group to which the author belonged, for the preparation of geological information needed to ensure stable supply of rare metal resources for Japan, and the Group has lived up to the expectations. The Group was expected to discover prospective deposits, prepare a base for processing tests, and construct a database. Research cooperation with many overseas geological surveys was carried out, and challenges were taken in regions such as South Africa that was remote and rife with difficulties. The author led and trained the Mineral Resources Research Group, and stood at the frontline of survey and negotiations. It is very valuable to place in *Synthesiology* this paper that describes the processes of survey, analysis and information, and provides an overview of rare metal resource research, particularly of rare earths. R&D at AIST toward resource development, collaboration with resource-producing countries, and a joint research framework with partner organizations are described with actual examples. A case study is presented for the measures against the rare earth crisis that was in the news recently, and important advice is given on procuring high-risk resources to ensure sustainable development of the Japanese industry in the future. Although resource development has high risks and requires a long time, the sense of crisis felt in the industry demand-supply and the international situation is not constant. This paper clearly shows the significance of continuing resource research on a long-term basis not only when the crisis is apparent, but also when it is latent.

2 Rare metal and rare earth

Comment (Yusaku Yano, Keizo Koyabashi)

The general readers have difficulty separating rare metals and rare earths. Since *Synthesiology* is not a journal for mineral resource specialists, can you state the definitions for rare metals and rare earths, and your thoughts on how the terms are used?

Answer (Tetsuichi Takagi)

The explanations of rare earths and rare metals were added at the beginning of this paper. In Japan, 31 metals are designated by METI as rare metals. They are separated from other metal resources, and measures are taken to ensure stable supply. Rare earth elements are handled as one of the metals among the rare metals, but, in practice, it is a general term for 17 metals including 15 lanthanide elements plus scandium (Sc) and yttrium (Y).

3 Resource research within the total effort by AIST for rare metals and rare earths

Question & Comment (Keizo Kobayashi)

I think AIST is working comprehensively on recycling, alternative material development, and usage saving technologies, not just resource development, as the measures for rare metals and rare earths. Also, I think you are spending effort (comprehensive and strategic) that is unique to AIST while considering the demand-supply balance of rare resources. From the perspective of the concept of full-scale research, I think there is an optimal technology with the industrial scenario in mind for each rare resource, but are rare earths the rare resources for which the resource development can be done most effectively? I think it will be more understandable if you describe how rare earth resource development is the most effective measure (considering the urgency and the realizability of alternatives), while showing us the comprehensive effort by AIST.

Answer (Tetsuichi Takagi)

I introduced the rare metal research at AIST in Subchapter 2.1. The research of rare metals can be roughly divided into materials science and earth science. In the former, the objective is the R&D for high-performance materials using rare metals, reduction of rare metal use, alternative materials, and recycling. On the other hand, in the latter, the objective is the exploration and evaluation of rare metal resources (the development of mineral processing and refining technologies span across both fields). Since AIST engages in comprehensive research of rare metals, the rare metal task force was set up in 2006, and research was the conducted in materials science and earth science as two wheels of a car.

Rare earths are one group of the elements where resource development is the most effective measure. The reason is its small consumption volume. For example, only a few hundred tons of dysprosium (a kind of rare earth element) that is essential in increasing the heat resistance of high-performance magnets is consumed annually in Japan. However, during the rare earth crisis, it became very difficult to obtain as the price skyrocketed, since almost all dysprosium was produced in the southern part of China. If a mine that produces dysprosium is developed outside of China, even if it can produce only a fraction of the consumed volume, the price increase can be controlled as the market principle starts to function. Also, since the mining facility can be small in scale, the production can be started quickly. For the same rare metals, the effect of resource development does not become apparent in a short-term period for the elements with relatively large consumption volume (such as nickel and tungsten), and it is necessary to comprehensively and concurrently promote the development of alternative materials and recycling technology.

4 Role of AIST in rare metal resource research and full-scale research

Question & Comment (Keizo Kobayashi)

You describe the position of AIST in resource development, the relationship with JOGMEC, and the relationship with resource-producing countries (their geological surveys), but it is a bit difficult to understand the roles of the related organizations in the resource development in the resource-producing countries. I think the measures taken are different for each country in doing resource development, but if you could describe the players' roles, I think things would become clearer in the framework of full-scale research.

Answer (Tetsuichi Takagi)

The roles of each player were described in Subchapter 3.2. In many cases, a single company or an official geological survey (AIST) engages in the phases of discovery of mineral occurrences, confirmation of ore deposits, and reconnaissance surveys. For the specific investigation phase, that is, drilling and geophysical exploration phase, the normal practice is for JOGMEC to do it alone or jointly with private companies, and then turn it over entirely to the private companies at an appropriate stage. The main developing company draws the specific development plan for the mine, conducts the environmental impact evaluation, and constructs the infrastructure, and the mine is opened only after all these phases. In the case of rare metal resources with high development risks, support by JOGMEC or JBIC may be necessary after the mine starts operation.

Question & Comment (Yusaku Yano)

What full-scale research is in rare metal resource research and how AIST contribute in overcoming the “valley of death” are the heart of this paper. Therefore, can you discuss them thoroughly?

Answer (Tetsuichi Takagi)

Seen from the perspective of rare metal resource (mine) development, in reality, the role of AIST is limited. There is a large organization called JOGMEC under METI, and the mining companies have their R&D divisions. Therefore, writing the scenario where AIST leads the way to overcome the “valley of death” in rare metal resource development will be overrating AIST. In this paper, we presented the concept of riding the wave of demand-supply for rare metals through the contiguous R&D at AIST. In Japan today, AIST is the only research institution that is capable of continuous and systematic information collection, survey research, and human resource training for rare metal and rare earth resources. The execution of R&D with medium- to long-term vision that is not affected by resource demands is the role AIST must take in full-scale research (Fig. 10). In preparation for the reaction against the lowered resource prices that will certainly happen in the future, AIST must be responsible in executing full-scale research.

The collaboration between AIST and the research institutions of resource-producing countries is an important pillar in executing full-scale research. There are many rare metal resources for which the international market has not been formed sufficiently, and because they are often targets of speculation, the reserve and grade of ores are often exaggerated in the disclosed information. To obtain accurate information, information gathering and joint survey with the official geological institution (geological survey) of the resource-producing country is necessary. AIST is a member of the International Consortium of Geological Surveys (ICOGS), and has built the cooperative relationship with geological surveys of major countries over the years. We were able to execute quick resource evaluation with South Africa, Mongolia, USA, and others during the rare earth crisis because of this cooperative relationship. We shall further promote collaboration with the geological surveys of resource-producing countries in the future.

Scenario in synthetic-type research: its role and description

— An investigation from *Synthesiology* papers —

Akira ONO[1*], Motoyuki AKAMATSU[2] and Naoto KOBAYASHI[3]

[Translation from *Synthesiology*, Vol.9, No.1, p.26-38 (2016)]

Synthetic-type research is conducted by private companies, public institutes, and universities to realize societal value by scientific and technological methods. *Synthesiology* is a scientific journal that enables authors to describe the processes and results of this kind of research. Editors specifically request authors to describe their scenario for synthetic-type research. In this paper, the characteristics of synthetic-type research are compared with those of analytic-type research, and the structures and properties of synthetic-type research scenarios are clarified. From the investigation of papers published in *Synthesiology*, we show that the scenario plays a central role in synthetic-type research and can be expressed using scientific languages.

Keywords **:** Synthesiology, paper, scenario, synthetic-type research

1 Introduction

Most people of today engaged in science and technology are strongly interested in how to effectively connect research and societal value for innovation. Much research is conducted by private companies, public institutes and universities, which is generally categorized into analytic- and synthetic-type research.

Analytic-type research is characterized as research whose major purpose is to discover knowledge elements and integrate those into a knowledge system after reducing nature and existence into their elements. Much of the research conducted at universities is of this type. Synthetic-type research is characterized as research whose major purpose is to create or produce things by integrating technical elements and synthesizing a goal. Much research conducted at private companies and public institutions is of that type.

Much synthetic-type research has been actually conducted in society so far. The writing format of the papers, however, has never been well established to express processes and results of such type of research. The journal of *Synthesiology* issued from 2008 is a new type of journal where processes and results of synthetic-type research are described.[1] The aim of issuing the journal is written in the Preface, "A journal of original papers of *Type Two Basic Research*,"[2] in Vol. 1, No.1 of *Synthesiology*. In accordance with this aim, this paper investigates the scenario that plays a central role in synthetic-type research.

Although the scenario of synthetic-type research is defined in Chapter 2, it may be said that the scenario is a kind of strategy to realize societal value by methods of science and technology, which is an important point for creating innovation. Authors describing processes and results of science and technology in the existing scientific journals, however, are not requested to describe the scenarios in their papers. The scenarios are not described often in the technical reports, "Giho," published by companies, either.

The Editorial Board of *Synthesiology* started the journal assuming that the scenario plays a central role in synthetic-type research and that it could be described by researchers verbally (using languages) and visually (using figures). Thus the editorial board requested the authors of the journal to describe scenarios in their own papers. This was an unprecedented attempt having never been made by the conventional scientific journals. *Synthesiology* has been published for eight years during which more than a hundred original papers have been issued.[1] We investigated those papers to see what role the scenarios played in synthetic-type research and how the scenarios were described verbally and visually. We attempted to see whether the assumption of the Editorial Board was valid.

In Chapter 2, characteristics of synthetic-type research are clarified in comparison with those of the analytic-type. Then the first hypothesis that the scenario plays a central role in synthetic-type research is presented.

In Chapter 3, the scenarios in synthetic-type research are described as having common and general characteristics. Then the second hypothesis that the authors of synthetic-

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type research papers can describe the scenario verbally and visually is presented.

In Chapter 4, investigations of papers issued in *Synthesiology* will show what role the scenarios play in synthetic-type research and how they are described verbally and visually. It is shown that there are different types of forms of expression of scenarios.

In Chapter 5, it is pointed out that the scenario can be effectively utilized for planning, implementation and evaluation of synthetic-type research.

See the paper, “Analysis of synthetic approaches described in papers of the journal *Synthesiology*,”[3] in Vo.5, No.1 of *Synthesiology* about the methodology of how technical elements are integrated and a goal is synthesized in synthetic-type research.

2 Synthetic- and analytic-type research

Science has developed very rapidly since the seventeenth century by understanding nature and existence by a method of reducing them into elements, i.e. the analytic approach. When we encountered complex issues like global environmental problems at the end of twentieth century, however, it became widely accepted that such issues could not be resolved only by the analytic approach.

Technology has developed very rapidly in the twentieth century with the endorsement of science. But it is evident that such technological development has not been conducted only by the analytic approach.

Consider the processes of synthetic-type research. Firstly, things or artifacts of societal value are identified to be realized. Secondly, goals of synthetic-type research are set to realize the societal value. Thirdly, the goals are broken down into technological requirements and elements. In this paper, research scenario (hereafter written just as “scenario”) is defined as that which, after breaking down the goal of synthetic-type research into technical elements, expresses logical relationship between the goal and the technical elements and that among the technical elements. The scenario of synthetic-type research may include not only items of science and technology but also frameworks like legislative systems, societal customs, human networks and joint research that may affect research implementation.

Researchers implementing synthetic-type research will take the processes of selecting, developing, and integrating technical elements, and synthesizing to achieve the goal, and then realize the societal value.

In this chapter, we create a hypothesis that the scenario plays a central role in synthetic-type research. The hypothesis will be tested in Chapter 4 by investigating the papers issued in *Synthesiology*.

2.1 Processes of scientific research and technological development

In this subchapter, we define scientific research and technological development separately as different concepts, each having its own methodology. Figure 1 schematically shows processes and results of scientific research in the upper part and that of technological development in the lower part.

The target of scientific research is nature and existence. There are individual disciplines in academic societies like physics, chemistry, biology, electrical and mechanical engineering, and medical sciences. A university student of the field of science and engineering sets his or her discipline for study

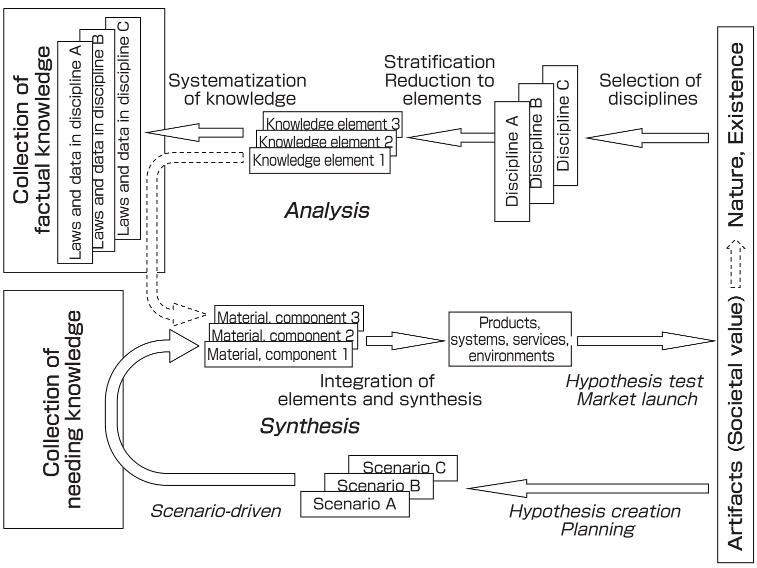

Fig. 1 Processes and output of scientific research and technological development

by selecting a department among others. A researcher also sets his or her profession by selecting a discipline. Each discipline has its own method of perspective and approach, based on which part of nature and existence is cut off in a specific aspect. A researcher finds pieces of knowledge of the discipline on the aspect cut off by stratifying phenomena and reducing them into elements. Discovered pieces of knowledge are systematized by relating them to each other, and then theories and formulas are established with the collection of data. In this sense the majority of scientific research is "analytic-type research" based on reducing into elements

The motivation of technological development is the will of a man to create something valuable for society. The value includes not only products and systems but also services and methods as well as protection and modification of the environment. As shown in Fig. 1 there are scenarios at the very beginning of processes to realize societal value.

Scenario making in the planning stage before implementation could be said to be hypotheses creation. Based on the scenarios or in scenario-driven ways, researchers of synthetic-type research select necessary materials, make components and elements, and synthesize target products, systems, services and environment. Since this process is a "synthetic" like process, the technological development could be said to be "synthetic-type research."

Demonstrating whether a synthesized artifact realizes the societal value targeted beforehand could be said to be hypothesis testing. In the case of private companies, realization of targeted societal value could be tested by introducing products or services into the market. In the case of research institutions and universities, realization of societal value could be tested by the reaction of society and industry to applied patents, proposed joint projects, manufactured prototypes, established databases and their disclosure for public use, published technical standards, developed metrological standards and reference materials and calibration services, developed geological maps and their publication, and developed risk evaluation methods and their applications.

When a synthetic-type research is conducted in the way shown in Fig. 1, success of the project of synthetic-type research depends on the quality of the scenario. This point is the first hypothesis created by this paper.

2.2 Interaction between scientific research and technological development

This subchapter describes the interaction between scientific research and technological development from historical examples in which research is connected effectively with societal value.

While science was born in the seventeenth century in western Europe, technology is supposed to have been born far beforehand around the time of the birth of human beings. Technology, which historically emerged way beforehand, and science, a newcomer, are basically different in nature, so effective interaction between the two may not be easy. Various attempts including those based on governmental science and technology policies are now being practiced around the world.

Interaction between science and technology began in the nineteenth century. A typical example is the relation between the invention of the steam engine and the development of thermodynamics. As shown by the upward broken-line arrow at the right hand side of Fig. 1, science recognized the artifact, the steam engine, as an existence and took it in as a research target. Resulting pieces and system of knowledge affected technological development to promote various thermal engines as shown by the downward broken-line arrow at the left hand side of Fig. 1. This is an example where science took results of technology in and then the technology was developed greatly by the endorsement of science. The science of neutrons and nuclear fission is strongly related to the technology development of nuclear weapons and power plants. Various discoveries in solid state physics and the invention of electronic devices including transistors are related in a similar manner.

An example in the twenty-first century may be nanotechnology. While nanoscience was a kind of observation science using electron microscopes at the beginning, the technological invention of scanning tunneling microscopes enabled not only observation but also manipulation of atoms, which led to processing and manufacturing various objects and structures at the nanoscale. Conversely, this stimulated science research to promote nanoscience. Nanotechnology is rapidly developing with the endorsement of nanoscience.

There may be similar relationship between life science and medicine and agriculture.

2.3 Attributes of synthetic-type research

Attributes of synthetic-type research compared with that of the analytic-type are shown in Table 1. The attributes of analytic-type research have been clarified over a long history of the establishment of science. The attributes in Table 1 for the analytic-type research can be considered accepted by all scientists. But the attributes of synthetic-type research have not been fully investigated because such type of research was defined quite recently.[1] Thus the following comments on the attributes of synthetic-type research are those of the authors of this paper at the present moment. (It is expected that they will be clarified in the course of time.)

The attributes in Table 1 are explained one by one.

Table 1. Attributes of analytic- and synthetic-type research

Category	Analytic-type research	Synthetic-type research
Methodology	Analysis	Synthesis
Action	Discovery and investigation of the truth	Invention and production
Knowledge	Factual knowledge	Needing knowledge
Motivation	Intellectual curiosity	Will to realize societal value
Scenario	Peripheral	Central
Discipline(s) involved	A single disciple	Plural disciplines
Uniqueness of solution	A unique solution	Plural equivalent solutions
Important characteristics	Consistency and systematization of knowledge	Societal value
Originality	Originality of factual knowledge	Originality of element selection and goal synthesis
Novelty	Novelty of factual knowledge	Novelty of element selection and goal synthesis
Evaluation	Peer review by experts	Merit review by beneficiaries

As the research names indicate, the methodology of research is analysis for analytic-type research and synthesis for the synthetic-type. The research conduct is discovery and investigation of the truth for the former, but is invention and production for the latter. The knowledge obtained is factual knowledge for the former about what the truth is, but is needing knowledge for the latter about what and how to do.

The motivation of obtaining knowledge is intellectual curiosity for analytic-type research, but is the will to realize societal value for synthetic-type research. The scenario of research is a peripheral interest and is not regarded as important for the former, but is regarded as most important for the latter being the central interest. The discipline involved in research is likely to be single for the former where specialization is usually intensified, while the disciplines involved are generally plural for the latter where necessary elements are taken in from many disciplines.

The solution is unique for analytic-type research where scientists believe that there should be a single solution of the truth. If there remain possible plural solutions for an issue, scientists continue to conduct research until a single solution remains. But there usually could be plural solutions for an issue for synthetic-type research that are equally important. The excellence of solutions depends on the societal environment and other relevant technologies, and has the possibility of varying with time.

The important characteristic is consistency among and systematization of knowledge for analytic-type research, but is societal value of research results for synthetic-type research. The originality is to create new elements of factual knowledge that the research adds on the system of existing knowledge for the former, but is to create new ways of selecting and structuring elemental technology for the latter.

The evaluation of research is made by experts being in the closest specialty to the authors for analytic-type research so that they can correctly evaluate consistency, systematization, and originality. This is called a peer review. However, for synthetic-type research, the evaluation of research is made by those who receive merit from the research results including researchers and engineers who receive merit from synthetic-type methods themselves. This is called a merit review. Reviewers of disciplines different from the author are usual.

3 Structures and properties of scenarios

In this chapter the characteristics of scenarios are generally investigated highlighting internal and stratified structures. Based on this investigation a second hypothesis that authors of synthetic-type research can describe the scenario verbally and visually is created. This hypothesis will be tested in Chapter 4.

3.1 Internal structures

While the processes of synthetic-type research are described in Fig. 1 using specific terms as materials, components, elements, we attempt to describe internal structures of scenarios using more general terms. It should be noted that a scenario is defined as “that which, after breaking down the goal of synthetic-type research into technical elements, expresses logical relationship between the goal and the technical elements and that among the technical elements.” It is supposed that the definition leads deductively to the internal structure of the scenario as shown in Fig. 2. Figure 2 is a kind of basic tool to be used for describing the scenario where the author(s) can establish the logical relationship between the research goal and technical elements

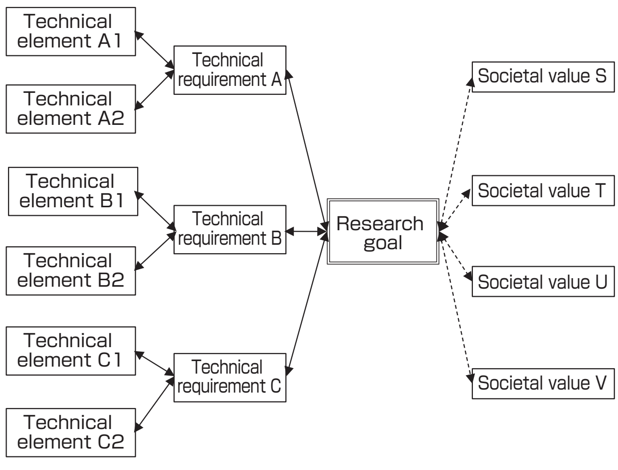

Fig. 2 Internal structure of scenario

When we follow the arrows in Fig. 2 from right to left, this is the process of scenario making. Assuming societal value in synthetic-type research, a researcher sets up a goal of research, which is an expected output of the research project. The goal of research is making goods, delivering services, and establishing methodology. (Those may be called generalized products.)

Next the goal of research is broken down into technical requirements. The technical requirements are often specific performances, characteristics, safety, expected life span, and manufacturing methods for production. Finally the technical requirements are broken down into technical elements. The technical elements are the basic units of the scenario.

When we follow the arrows in Fig. 2 reversely from left to right, this is the process of scenario implementation of synthetic-type research. Firstly, taking into consideration the technical requirements, the researchers seek technical elements and select the most suitable ones for the research project. If critical technical elements are unavailable, the researcher attempts to develop new techniques. Next, the researcher attempts to achieve the goal of research by integrating the technical requirements. Finally, whether the achieved goal of research meets the societal value set in the scenario making is verified and evaluated.

3.2 Stratified structure

Synthetic-type research could be of different sizes. The scenario could be at different levels, e.g. from a small and simple scenario like at the very beginning of a research project to a large and complex scenario like at the final stage of a project. A large-size scenario may be composed of small-size scenarios as shown in Fig.3. Those scenarios have the same internal structures independent of the size, i.e. there is similarity. A larger-size scenario embraces smaller-size scenarios.

In stratified structures, a goal of smaller-size research could contribute to a larger-size one as one of the technical elements. Thus scenarios may be said to have similarities having fractal structures.

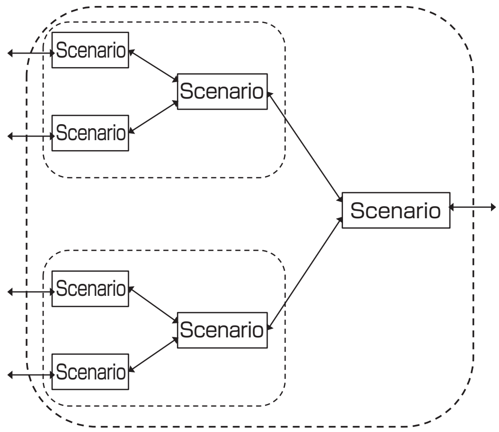

Fig. 3 Stratified structure of scenario

Table 2. Extracted instruction to write *Synthesiology* papers

	Item	Requirement
1	Research goal	Describe the research goal (“product” or researcher’s vision).
2	Relationship of research goal and society	Describe the relationship of research goal and society, or its value for society.
3	Scenario	Describe the scenario or hypothesis to achieve the research goal with “scientific words.”
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.
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.”

Assuming the internal and stratified structures of scenarios, researchers of synthetic-type research can describe the logical relationship between the goal of research and technical elements in terms of science and technology. This is a second hypothesis the present paper creates.

4 Description of scenarios in *Synthesiology* papers

The Editorial Board of *Synthesiology* requests authors to describe their own scenarios in the papers. In this chapter, we investigate how the scenarios are described by the authors. Then the two hypotheses created in Chapter 2 and 3 will be tested.

4.1 Request for description

Table 2 shows an extracted instruction in the Editorial Policy[4] of *Synthesiology* about how to write *Synthesiology* papers. The third item, “Scenario,” characterizes the journal. Thus the Editorial Board requests authors of *Synthesiology* papers to describe their own scenarios.

4.2 Common characteristics

We found some common characteristics of scenarios regardless of discipline by reading the papers published in *Synthesiology* and by interviewing the authors.

4.2.1 Birth of a scenario

An “idea” or a “flash of thought” of a researcher could provide an opportunity for the birth of a scenario at the early stage of research even if it develops into a large-scale project. The idea or the flash of thought may change to a “possibility” and could grow into “conviction” in the researcher. Then discussions of a scenario with his or her colleagues may promote expressing the scenario verbally and improving the logic of the scenario, which helps it to evolve so that a third party can understand.

Thus a prototype of a scenario is grown within a researcher’s head at an early stage without expressing in a language and improving the logic. His or her research colleagues could join a collective activity of research only after the stage of expressing the scenario in a language. There is no means to communicate the scenario to others before the stage of expressing in a language when the scenario remains just as an idea that is hard to express.

4.2.2 Change of a scenario over time

The scenario develops step by step for improvement as the research progresses and the research group discusses. It is usual with the *Synthesiology* papers for the author(s) to describe scenarios of the time when the author(s) writes the paper or the “last” version of the scenario which he/she reaches in the end.

The *Synthesiology* authors often describe scenarios changing over time as the research project develops. Then a few scenarios are described in the paper with a stratified structure as shown in Fig. 3. The project started later takes in the results and experiences of the project started earlier where the later one sets up the goal that is closer to the societal value.

4.2.3 Large-scale scenarios

In the case of large-scale projects where many researchers are involved, the scope of research becomes quite wide with stratified scenarios. Research groups are formed for individual areas of technical requirements usually with several researchers involved for each area. Experts would be individually involved for each technical element. Stratified scenarios as shown in Fig. 3 are usually made.

4.2.4 Describing scenarios in language

The following was found from interviews to the authors of *Synthesiology* papers. When researchers are actually conducting research, they may conceive their own scenarios in an intuitive or unconscious manner. Such scenarios are not often left on record and have no written documents. In such cases some authors realized that they had actually conceived intuitive scenarios unconsciously when they started writing the *Synthesiology* papers. There were more than a few papers in *Synthesiology* where intuitive scenarios were written in language probably for the first time.

When researchers did not record their scenarios in a written form, it seemed considerably hard for them to recall the scenarios from the past and reproduce the processes of developing the scenarios. As the scenarios change and develop over time, the past scenarios are likely to disappear from the researchers’ memory.

4.3 Various forms of scenarios

It is supposed that the internal structure of the scenarios the *Synthesiology* paper authors have is basically like Fig. 2. However the forms of scenarios were quite different from author to author about what aspects of the logical relationship between technical elements are emphasized. Some scenarios described in the *Synthesiology* papers are summarized in Reference [5]. We categorized those forms into four types.

4.3.1 Logical relationship between technical elements

About 50 % of the *Synthesiology* papers illustrate the logical relationship between technical elements in a similar form to Fig. 2. In these papers technical elements and technical requirements are logically related and a goal of research is achieved by integrating them.

An example of this type is the paper, “Investigation of the distribution of elements of the whole of Japan and their applications,” in *Synthesiology* Vol. 3, No.4.[6] The scenario is illustrated in Fig. 4. The goal of research was to investigate distribution of elements on the surface of the earth crust of the whole of Japan and to make a map of element distribution (a kind of geochemical map) and open it to the public. To understand environmental pollution by toxic substances like arsenic, mercury, cadmium etc. and to seek the origin of the pollution were also intended.

Because the geochemical map is a kind of database, the scenario set five technical requirements for the database of basic characteristics, completeness, reliability, user convenience, and operability. A certain level of quality is required for each necessary condition for the geochemical

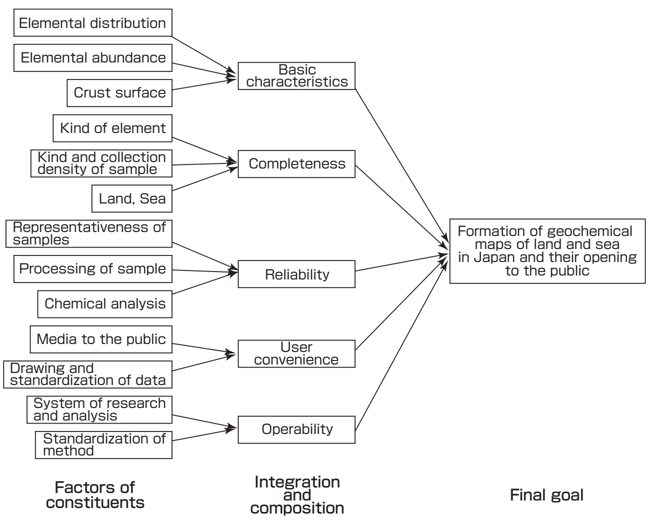

Fig. 4 Formation of the geochemical map of Japan and a scenario for opening access to the public
(From N. Imai, *Synthesiology*, Vol.3, No.4 [6])

map to be used widely by society. Then thirteen technical elements were set as shown in Fig. 4 to meet the quality of technical requirements. Actual research activities were the development of the technical elements, field work and chemical analyses of samples.

The biggest issue of this project was the completeness of the database. Under the restrictions of the number of participating researchers and time frame of research, the sampling density of one for 10 km square had to be selected. The biggest issue was whether the geochemical map of such low density sampling would be accepted by society. However low density sampling was decided. The project was started so that the technical elements and technical requirements were achieved within the preset time frame. In this way the element distribution map of the whole of Japan including both of land and sea was completed. At present this geochemical map is being used widely, overcoming the problem of sampling density.

4.3.2 Cyclic relation among technical elements

About 12 % of the *Synthesiology* papers illustrate the cyclic relationship of logic among technical elements, where time variation of the research project is incorporated in the scenario. Industries and societal sectors are allocated as partners of research. Research results obtained are provided to the partners step by step, and research is developed gradually by using information obtained from the partners. The *Synthesiology* paper, “Technologies for the design and retail service of well-fitting eyeglass frames,”[7] in Vol.1, No.1 is a typical one, the scenario of which is shown in Fig. 5.

The shapes of the face and the head are quite different according to individuals. Taking this into account, the goal of this research was set to establish a framework for an eyeglass shop so that the shop can provide customers with eyeglass frames best-fitting to individual head shapes of eyeglass users.

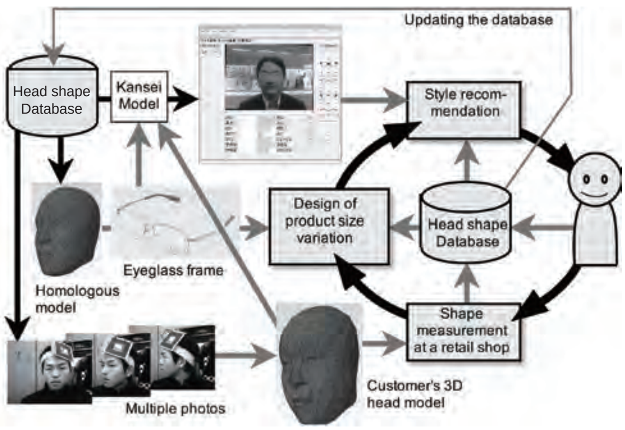

Fig. 5 A system to produce eyeglass frames according to the “Finding well-fitting products” approach
(From M. Mochimaru *et al.*, *Synthesiology*, Vol.1, No.1 [7])

Four technical requirements were set. They are the head shape database composed of many people, head shape measurement of customers at retail shops, design of eyeglass size variation, and style recommendation service. The head shape database is the center of this research because containing as much head shape data in the database is the key to providing customers with better eyeglasses.

This scenario is characterized by the cyclic flow of actions and data that circulate across technical requirements under the collaboration between researchers and the retail shops and customers, i.e., their partners. The head shape database becomes larger and better as more customers visit the shop. The scenario of the synthetic-type research is quite unique where actions and data circulate around a database across technical requirements.

4.3.3 Selection of technical elements

When a researcher of synthetic-type research sets up technical requirements and technical elements, the best elements are selected from existing ones and, if appropriate elements are not found, new ideas have to be created. About 13 % of the *Synthesiology* papers illustrate the processes of element selection. Those papers actually describe decision making processes of the authors where possible choices of elements are compared and evaluated from scientific and technological points of view on merits and demerits.

The *Synthesiology* paper, “Mass preparation and technological development of an antifreeze protein,”[8] in Vol.1, No.1 is a typical one. The scenario is shown in Fig. 6 where choices from various possible elements and the authors’ decision processes are described.

An antifreeze protein has the effect that the freezing temperature of its water solution is depressed below 0 degree Celsius. It is known that such proteins exist in creatures living in the cold regions of the earth. Industrial applications of antifreeze proteins were highly desired, but the difficulty was the lack of amount of purified antifreeze proteins for practical use. The authors’ scenario was to take the following

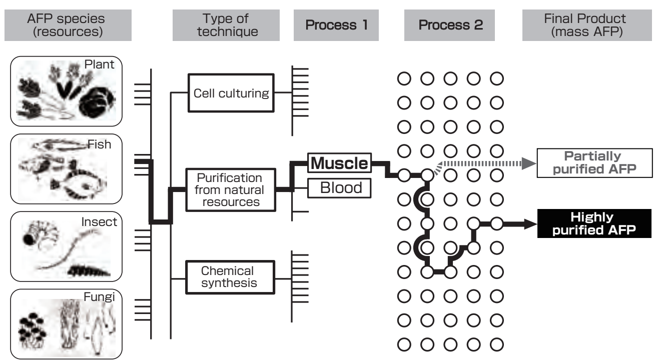

Fig. 6 Procedure for obtaining mass amount of AFP
(From Y. Nishimiya *et al.*, *Synthesiology*, Vol.1, No.1 [8])

choices to overcome the difficulty. First of all, the authors chose fish from among many kinds of creatures containing antifreeze proteins in their bodies. Secondly, they made the choice of purification of antifreeze proteins from natural resources (fish) instead of cell culturing and chemical synthesis. Thirdly, they made the choice to purify antifreeze proteins from muscles of fish instead of blood. These choices were made based on both the authors' scientific knowledge and intuition. This resulted in the success of the production of purified antifreeze proteins to a practically sufficient amount from the muscles of small fish unloaded at the ports in Hokkaido. Now the authors and private companies collaborate for industrialization.

The *Synthesiology* paper tells us that the important points in research are the positions of not necessarily prioritizing the current trend and of respecting basic research to get scientific knowledge necessary for making choices.

4.3.4 Changes over time

The scenario sometimes can be changed greatly including modification of the research goal when synthetic-type research itself evolves in an unexpected way, societal environment of the research changes, and a new technical element affecting the research emerges.

It is rather natural that the scenario of a long-term synthetic-type research changes during implementation. About 20 % of the *Synthesiology* papers illustrate how the scenario changed.

Figure 7 is an example of such a paper illustrating a series of scenarios about a real-time all-in-focus microscope from the early stage of the research to the industrialization stage.[9] An idea of a new microscope emerged from a scientific interest, the idea evolved during the implementation of research and, the research goal was clarified and specified step by step through the development of new technical elements and through communication with a collaborative company. The *Synthesiology* paper describes the whole story of a long project, where we can understand the dynamism of synthetic-type research.

4.4 Difficulties in scenario description

There are some *Synthesiology* papers where scenarios are not described explicitly. There may have been the following reasons behind that.

A) The key point of the writing form of *Synthesiology* papers was not well explained to the authors by the Editorial Board. This led to the authors writing their *Synthesiology* papers without fully understanding how to describe the scenario specifically.

B) Individual members of the Editorial Board had more or less different ideas on the form of the scenario of *Synthesiology* papers because it had not been well established.

C) Review criteria for the reviewers were not well established. This might not have guided the authors well on how to specifically describe their scenarios.

Circumstances of A) to C) seem to have been unavoidable because the study of the writing form of synthetic-type research papers just started ten years ago, and is still continuing. As it took a very long time from the seventeenth

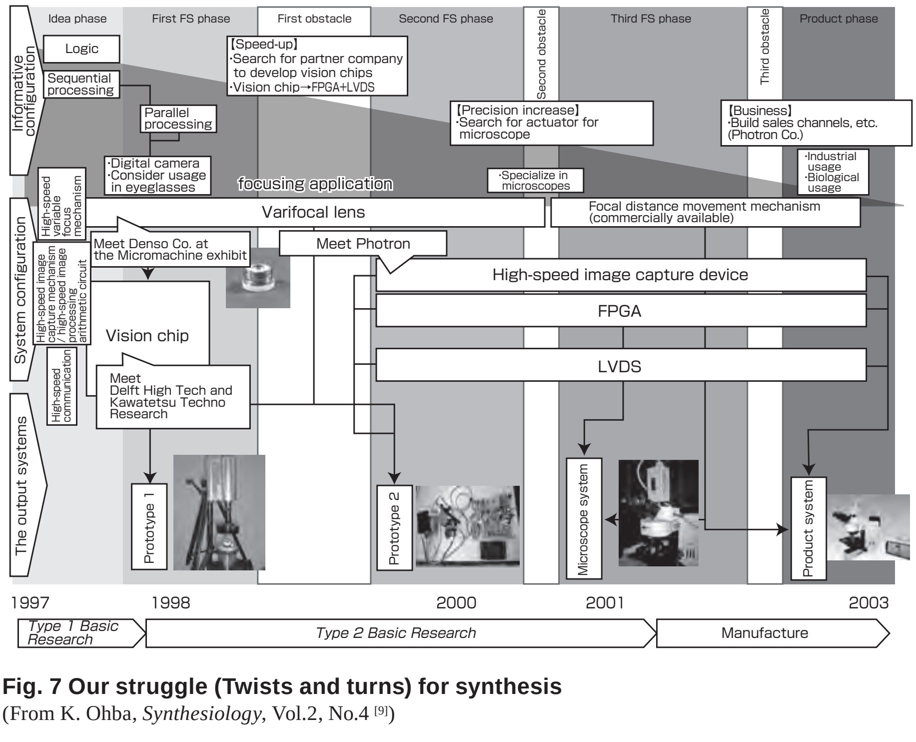

Fig. 7 Our struggle (Twists and turns) for synthesis
(From K. Ohba, *Synthesiology*, Vol.2, No.4 [9])

century for the form of analytic-type research papers to be well established, it is understandable that the writing form and review criteria of synthetic-type research papers are not well established at the moment. This problem will be resolved step by step through further publishing of *Synthesiology* papers and through experiences of writing papers on synthetic-type research.

4.5 Hypotheses testing

The Editorial Board of *Synthesiology* requested the authors to describe their own scenarios of synthetic-type research, based on two hypotheses that the scenario would play a central role of synthetic-type research and it would be possible to describe the scenario verbally and visually.

Almost all *Synthesiology* papers mention scenarios explicitly or implicitly. In most cases specific chapters, sections and columns are allocated for scenario description. The scenarios cover the whole of research and describe logical relationship of research contents.

Most of the *Synthesiology* paper authors quote their own past papers published in other refereed journals. The scenarios of *Synthesiology* papers are written in a way that goes right through their past papers. The scenarios usually reveal the relationship among those papers. It is supposed that the scenarios are like an axis running through a series of their past papers. Interviews to some of *Synthesiology* paper authors were also supportive showing that writing *Synthesiology* papers was a good chance for the authors to review a series of their own research and reconfirm the essence of the research.

The scenarios of the *Synthesiology* papers vary widely in scale from a large-scale project involving a whole technical field to a small-scale one of just one researcher. However the importance of scenarios in synthetic-type research, whatever the scale, seems equivalent.

From the *Synthesiology* papers, one can say that, if the scenarios were deleted from the papers, those papers would become just collections of research results obtained from the past papers. It would lack the essence of the authors' intentions, i.e. the axes across a series of their past research. Thus it could be said that what characterizes the *Synthesiology* papers is the scenario.

Thus, with respect to the first hypothesis, it could be said that the scenario plays a central role in synthetic-type research.

More than half of the *Synthesiology* papers illustrate the scenario or something equivalent to that using one or two figures. Those figures show on what scenario the authors conducted synthetic-type research, and the overview of the logical relationship between the research elements. Detailed logical relationship between the research goal and technical elements is also described in the text of *Synthesiology* papers.

In *Synthesiology* papers, the authors describe scientific and technological items and frameworks at a certain balance, although different according to individual papers. While some papers describe only scientific and technological items, others stress frameworks. The most typical framework is collaborative research. The reason is that much synthetic-type research has been conducted in a collaborative way between public institutes and private companies, most of which can result in success. It is supposed that the difference of emphasized items comes from the authors' view on what the most important factor was for success of research.

It was noted in Subchapter 4.3 that the scenario is described in various forms. Figure 4 shows that the internal structure of the scenario shown in Fig. 2 can be used as is as a descriptive form of logical relationship. Figures 5, 6 and 7 emphasize specific aspects of logical relationship between elements. In these cases technical elements and technical requirements are described in more detail in the text and other figures.

All the scenarios described in *Synthesiology* papers are original creations in the sense that they are described for the first time by the authors. The example of a scenario shown in Fig. 5 further indicates that a new methodology of research was created by inventing a cyclic relationship between technical requirements. High originality is recognized in the scenario itself.

Round-table discussions were held twice with the authors of *Synthesiology* papers and members of the Editorial Board to talk about their experiences of writing *Synthesiology* papers.[10][11] There is an author of a *Synthesiology* paper who submitted an article to *Synthesiology* again that reviews hisSynthesili synthetic-type research as a whole.[12] The round-table discussions and the article also support the second hypothesis.

Thus, with respect to the second hypothesis, it could be said that the scenario can be described verbally and visually throughout all disciplines and all scales of projects, although in quite different forms from author to author.

5 Applications of scenarios

Since the scenario plays the central role in synthetic-type research, it would be reasonable to expect that the scenario is useful in various aspects of such type research. Possibilities in scenario use will be discussed below in planning, implementing, and evaluating synthetic-type research. It is suggested that there may be possibilities that the speed of synthetic-type research for innovation could be remarkably increased in society through disclosing and sharing of scenarios.

5.1 Planning of a research project

A project plan can be made based on a scenario rearranged to meet limitations of resources such as time period, budget, manpower, and equipment. The scenario can be used as follows.

5.1.1 Setting-up of research goals

When a project planner sets up the purpose of a research project, the planner can integrate the societal value in the scenario into the project. There is an option of taking the societal value as is in the scenario, focusing on a specific value in the scenario, or adding some other value to the scenario.

5.1.2 Application to a roadmap

A project planner can add time priority to the scenario and develop it into a project roadmap.

5.1.3 Development of technical elements

A project planner can make an implementation plan of a project by selecting necessary elements from the scenario. If there is a lack of technical elements necessary to achieve the goal, the project planner identifies them and makes a decision whether to develop them internally or to outsource development.

5.1.4 Communication with potential stakeholders

If a project planner communicates with potential stakeholders like private companies similarly interested in the scenario, the project planner can receive feedback concerning the scenario from the potential stakeholders for improvement. When a private company is further interested in research implementation, the project planner and the company can discuss in detail the possibilities of collaborative research identifying each other’s roles in the scenario.

5.1.5 Estimate of resources

A project is applied by a planner for endorsement or funding to its own organization or research funding agencies. The application could be improved if the project planner estimates necessary resources (manpower, equipment, money, and time) correctly based on the scenario.

5.2 Implementation of research projects

5.2.1 Framework formation for research implementation

According to individual roles of scenario elements, the project leader can specify participating researchers appropriately. The project leader can select external partners, if necessary, to establish collaborative research of a larger formation.

5.2.2 Formation of participating researchers

The project leader ensures that all the participants in the research project share the scenario and understand their individual positions and roles. In the case of industry-academia-government collaboration, individual participants can clearly recognize through the scenario their own roles and relationship to each other in the project beyond the formation.

5.2.3 Changes of a research project and formation

When a research project has to be changed halfway by an interim evaluation etc., the project leader can change the research project in a consistent and flexible manner if he or she makes changes based on the scenario.

5.3 Evaluation of research

5.3.1 Evaluation of research projects

A research evaluator of research funding agencies etc. can evaluate an applied project based on the scenario of synthetic-type research. The decision of adoption or rejection of a research project is made appropriately through reviewing the scenario in terms of rationality, innovativeness, and feasibility, as well as validity of resource requirements.

When an interim evaluation of a research project is made halfway, a research evaluator can evaluate the progress of the project in comparison with the original scenario and can appropriately evaluate a proposed change of the project due to environment changes based on the scenario.

At the final stage of a research project, a research evaluator can appropriately evaluate processes and output of a project based on the scenario.

5.3.2 Evaluation of the scenario

The success of synthetic-type research strongly depends on the quality of the scenario because it plays a central role in such type research. Thus it would be important to evaluate the quality of the scenario in terms of rationality, innovativeness, and feasibility. It should be noted here that not all synthetic-type research directly reach societal value. As shown in Fig. 3 a small-size scenario allocated at a lower position reaches societal value through some other larger scenarios. So the validity of the “chain of scenarios” to reach the societal value should also be evaluated.

The evaluation of the scenario should be made from the following points of view.

a) Is the assumed societal value appropriate from the viewpoint of the present and future society and industry?

b) Is the research goal targeted effectively and inevitably for the realization of the assumed societal value?

c) Is the scenario described appropriate from the viewpoint of the targeted research goal? Has the realization of societal value been well considered in the scenario?

d) Does the scenario show clear superiority over others from the viewpoint, for example, of the possibility of a breakthrough?

e) Are the technical requirements broken down necessary and sufficient from the viewpoint of the research goal?

f) Are the identified technical elements necessary and sufficient from the viewpoint of technical requirements?

g) Are the identified technical elements available?

h) If there are unavailable technical elements, are the possibilities of self-development or outsourcing to other organizations well considered?

5.3.3 Improvement of evaluation quality

A project plan of synthetic-type research is usually described in an application form submitted to a research funding agency. The project plan is evaluated for the decision of adoption or rejection. Research output of a project is described in a final report after finishing all research activities. The application and final report are submitted to the same agency, but separately at different times. Thus it would not be very easy for the project leader to check the validity and rationality of the research over the whole period from the application to the finish. It would require considerable effort for a funding agency to evaluate in a coherent manner a research project over the whole period. A research evaluator could evaluate the processes and results of research more appropriately if a scenario is available at the application time and if a scenario reviewed or revised is available at the interim time.

The success of a research project is judged by its output in quality and quantity. Papers published in refereed journals are used as objective evidence. However, it should be noted that, even if a paper of synthetic-type research is submitted, most academic journals expect authors to write papers in the form for analytic-type research and reviewers of papers apply the review criteria for such type research.

At the moment there are very few refereed journals that receive papers of synthetic-type research. The first reason is that submission of synthetic-type research papers is beyond expectations to most of the refereed journals. The second reason is that researchers of synthetic-type research do not know how to describe processes and results of such type research well. The third reason is that reviewers of most of the refereed journals do not have clear review criteria for synthetic-type research.

Appropriate research evaluations would be made if more and more papers of synthetic-type research are published in many refereed journals including *Synthesiology* where processes and results of such type research are described. Submission of synthetic-type research papers is strongly encouraged.

5.3.4 Evaluation of researchers

It would become possible to find good researchers who can conduct synthetic-type research well and to evaluate such capabilities when many scenarios become open to the public. Also researchers of synthetic-type research can know themselves what capabilities should be obtained for innovation creation.

The following is the basic capabilities required for researchers of synthetic-type research.

a) Capability of assuming new societal value

b) Capability of targeting a research goal to meet societal value

c) Capability of describing an entire scenario from the research goal to the technical elements

c-1) Capability of breaking down the technical requirements into performance, characteristics, safety, risk etc. to achieve the research goal

c-2) Capability of identifying technical elements necessary and sufficient to meet the technical requirements

c-3) Capability of recognizing the strength of technical elements his/her research group owns, and finding/selecting excellent technical elements that preceding researchers own

c-4) Capability of finding/selecting technical elements useful to his/her own purposes that have been already realized in other disciplines

c-5) Capability of developing key technical elements that have never been realized

6 Conclusions

We investigated more than a hundred *Synthesiology* papers. It was confirmed that the scenario plays a central role in most of the *Synthesiology* papers. The scenario description is the greatest characteristic of *Synthesiology* papers that is different from other scientific journals. About two thirds of the *Synthesiology* papers describe the scenario or something equivalent visually using figures. It was also confirmed that the scenario can be described verbally and visually.

Although the skill of describing the scenario varies from paper to paper, the form of the scenario will be refined in the future as experiences are gained. This time the hypotheses were tested within the limited materials of more than a hundred *Synthesiology* papers. In the future, the testing is expected to become more reliable if more synthetic-type research papers follow.

It was a surprise that the *Synthesiology* papers were described in an intelligible manner to reviewers and readers of the journal whose disciplines are different from that of the authors. While almost all papers published in the contemporary scientific journals are not intelligible to those whose disciplines are different from those of the authors, it is remarkable that the *Synthesiology* papers are comprehensible. If the writing form of synthetic-type research papers becomes more refined, *Synthesiology* papers will become more understandable to readers.

Interviews to the *Synthesiology* paper authors revealed that the discussion with reviewers was quite useful to the authors. Discussions with reviewers were open to the public readers with the real names of reviewers revealed, which was a new attempt. The discussion with reviewers is considered quite helpful for the readers to understand the papers better because the reviewers ask important matters that the authors may have missed.

In the early 2000s, AIST conducted "*Full Research*" which is composed of *Type 1 Basic Research*, *Type 2 Basic Research* and *Product Realization Research* in a concurrent and coherent manner.[13] *Type 2 Basic Research* and *Product Realization Research* may be equivalent to synthetic-type research while *Type 1 Basic Research* to analytic-type research.

Results of synthetic-type research are usually published in the journals of industrial associations and the reports of individual companies (Giho). But the scenarios, i.e., the present central issue, are not fully described there. If a researcher of synthetic-type research wants to submit a paper to scientific journals, the researcher has to write a paper in the form of analytic-type research so that the materials have to be considerably rearranged to meet the review criteria of journals for analytic-type research. In this environment it is quite difficult to describe scenarios of synthetic-type research in the existing scientific journals.

The scenarios of synthetic-type research will be widely shared in and become important assets of society if scenarios are published more not only in *Synthesiology* but also in other journals. When a scenario is shared by different disciplines, then it is expected that a new collaborative research region is temporarily created that may be thought of as a new converging discipline. When a scenario is shared by industry-academia-government collaboration, then it is expected that a new collaborative research region is temporarily created that is across different organizations. Generally there are many difficulties in collaboration between different disciplines and between different organizations. If a common scenario were to be shared and understood by all the participants, then the level of collaboration and the speed of research would be remarkably increased.

Sharing scenarios between different disciplines and organizations benefits not only organizations implementing research but also the funding agencies through appropriate evaluations and more effective funding.

The importance of synthetic-type research will be increased in the innovation age. There probably were excellent scenarios behind the creation of excellent societal value. It is expected that research and societal value are connected more efficiently by disclosing and sharing scenarios as societal assets. Sharing scenarios will inspire researchers and research groups in industries, universities, and governments. The frameworks of research in society will possibly evolve into a new stage where research is remarkably accelerated for innovation.

Acknowledgements

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Discussions with Reviewers

1 General comment

Comment (Hiroyuki Yoshikawa, Japan Science and Technology Agency)

I consider that this paper is useful for quality improvement of *Synthesiology* papers to be submitted in the future and for better understanding of the readers of this journal because it deals with important issues on the papers published in *Synthesiology*. The submitted *Synthesiology* papers contain original knowledge about synthesis obtained during actual research. The authors of synthesiological papers have to seek a logical structure of writing a paper themselves while those of general scientific papers can write papers in a traditionally established way. In this sense it is valuable that the logical structure of a paper is examined by surveying the submitted papers.

This paper may be considered as the analysis of evidence because evidence was obtained from detailed survey of about a hundred published papers. If so, this paper would firstly describe revealed facts and secondly present analyzed results, which would show what the synthesiological papers are like. Then this paper would become like an analytic-type paper, which may not be very suitable for the journal of *Synthesiology*. Instead, however, the authors of this paper actually created hypotheses on the writing form of synthetic-type research papers having been in the position of planners of the journal. The hypotheses have been tested, and plenty of new contents have been obtained that were not clear at the planning stage of the journal. So this paper can be considered as contributing much to the writing of *Synthesiology* papers in the future. I highly respect the authors' will of not writing the paper like an analytic-type research one. It impresses me.

It is suggested to the readers of this paper to see Kobayashi's paper in Vo.5, No.1, *Synthesiology*.[3]

Comment (Noboru Yumoto, AIST)

The first version of the manuscript described the methodology of synthetic-type research in comparison with that of the analytic-type and how to make a scenario of synthetic-type research referring to the published *Synthesiology* papers. However, it is thought that this paper does not develop its original contents sufficiently to be accepted as a research paper of *Synthesiology*.

It was highly evaluated that the authors made an effort to widely revise the first manuscript to clarify the hypotheses and their test in the second version. It is very valuable to test the two hypotheses because they have been assumed at the start of *Synthesiology*; the first being that the scenario plays a central role in synthetic-type research and the second being that it would be possible for the authors to describe the scenario verbally and visually in their papers. However I think that it is necessary to consider carefully the fact that all the authors of published *Synthesiology* papers were requested to describe the scenario, which may have given a potential bias to scientific testing of the hypotheses.

I think that, as explained in the authors' answer to the second round review, examinations are important from the viewpoint of hypotheses testing why there are some papers that do not describe scenarios clearly. Inclusion of such examinations in the text of this paper is requested.

Answer (Akira Ono)

The first version of the manuscript emphasized too much how to make scenarios. So it was revised not to emphasize it because every scenario is an original creation of the authors of *Synthesiology* papers and because it is actually difficult for a third party to instruct the authors on how to make their scenarios. The authors of this paper also thought that the first version lacked a clear description about creating and testing hypotheses. So Subchapter 4.5 "Hypotheses testing" was newly introduced to describe it in more detail.

While synthetic-type research actually has a long history, the writing form of such type research papers had never been investigated until ten years ago, when *Synthesiology* was issued for the first time. On the other hand, the writing form of analytic-type research papers has been developed over a long time since the seventeenth century, and has become common knowledge accepted by all scientists. Compared with that, the writing form of synthetic-type research papers is far from established, and its verification has never been universally demonstrated. It will take much more time to demonstrate the two hypotheses thoroughly. Thus we made revisions to the manuscript from the viewpoint of what can be said from the several-year experience we have had with *Synthesiology*.

We would like to tell our thoughts on a potential bias that the *Synthesiology* paper authors may have received. The Editorial Board actually attempted to instruct *Synthesiology* paper authors in advance for better writing, for example, by introducing scenarios having been described in the past published papers. But we think that the essential points of hypotheses testing are, regardless of Editorial Board instructions, the questions of whether the scenario "intrinsically" played a central role in synthetic-type research and of whether it was "intrinsically" possible for the researchers to describe scenarios verbally and visually. The contents of scenarios are entirely original of the authors, which are not anything resulting from the instructions of the Editorial Board. The hypotheses testing was done not through whether a chapter for scenario description is set or not but through investigating the "intrinsic" validity of the hypotheses by reading the *Synthesiology* papers.

The authors' consideration was described in a new Subchapter 4.4 "Difficulties in scenario description" about why there were some papers that did not describe the scenarios clearly.

2 Difference between analytic- and synthetic-type sciences

Comment (Hiroyuki Yoshikawa)

Figure 1 illustrates the difference between the analytic-type sciences and synthetic-type ones, but the relation to the general explanation is not easy to understand. The general explanation is like this: While in analysis, one creates (derivation of laws) and develops (collection of knowledge) a discipline to explain nature and existence, in synthesis, one creates methods to get existences (products, services, and methods) or actually creates them to realize given expectations or value. The analysis and synthesis have parts in common logically, but the logics appear in different orders. The scenario of synthesis is hypothesis creation while the discovery of laws is hypothesis in the analysis. However, the processes of hypothesis creation are not supposed to be written in papers of the analysis. The synthetic-type science papers are different from general scientific ones on the point that the scenario is highlighted and explained. That is the difference of the analytic-type sciences and the synthetic-type ones. Please add a figure that explains the difference visibly.

Answer (Akira Ono)

We agree with your view on the hypothesis creation in the synthetic-type sciences. Figure 1 was replaced with a revised one which shows more clearly the suggested relationship between the analytic-type sciences and the synthetic-type ones.

3 Internal structure of scenarios

Question (Hiroyuki Yoshikawa)

Figure 2 is explained in this paper as showing the scenario making processes of synthetic-type research with the arrows from right to left, and the scenario implementing processes of such type research with the arrows in the other direction. The explanation could be read like this. "Relation figures like Fig. 2 already exist probably with huge data of technical requirements and elements, from which appropriate elements are carefully selected to integrate and synthesize products of real existence." My question is the following. In the published *Synthesiology* papers, were relation figures like Fig. 2 formulated places of scenario making given by existing data? Or, in most of the cases, were relation figures like Fig. 2 actually created in the processes of scenario making without such data? If the goal of *Synthesiology* is to establish general formulation of scenarios, it is suggested to emphasize that the individual *Synthesiology* papers are examples of evidence, collection of which may lead to a general form of Fig. 2.

Answer (Akira Ono)

Figure 2 illustrating the internal structure of a scenario and the logical relationship was deduced by the authors from the definition of the scenario at almost the same time as the issuing of *Synthesiology*. Figure 2 is a basic form explaining the logical relationship between the research goal and technical elements in the scenario.

We agree that in many cases relation figures like Fig. 2 were created without existing data by the *Synthesiology* paper authors in the processes of scenario making. If we look at the *Synthesiology* papers in detail, none of the scenarios appear similar. This means that the logical relationship describing their scenario in the most appropriate way is not necessarily the same as Fig. 2. Examples are shown in Subchapter 4.3 "Various forms of scenarios." We think that Fig. 2 could be instructive for researchers of synthetic-type research to describe their scenarios, but the most appropriate forms may be different from author to author. It will be useful to collect examples of forms of scenarios and categorize them.

4 Definition of the scenario and its role

Comment (Hiroyuki Yoshikawa)

Please define the scenario clearly. While the importance of the scenario is explained sufficiently in this paper, what the scenario does is not. When reading this paper, I began to feel that my understanding had not improved of what a scenario is and why it is necessary to write a scenario. This paper provides many explanations about the role of the scenario stating its usefulness, but it does not lead to the absolute necessity of the scenario. On the other hand this paper mentions the necessity of the scenario to some extent using examples in Chapter 4. In Section 4.2.4 “Describing scenarios in language,” for instance, it is said that the scenario description is necessary as record keeping. However, verbalization of the scenario is not just for records but is needed to help discover logical relationship between the technical elements which is intrinsically part of societal value and research goals but is not expressed. If a positive explanation could be clearly given why the scenario written in language is necessary, the significance of this paper as well as of synthetic-type research could be better understood.

Answer (Akira Ono)

Since the definition of the scenario was not clear in the first version of manuscript, it was revised, and the definition was given at the beginning of Chapter 2 as “that which, after breaking down the goal of synthetic-type research into technical elements, expresses logical relationship between the goal and the technical elements and that among the technical elements.”

We think that the reason why the scenario has to be described in language is to make clear the logical relationship between the research goal and technical elements and that among the technical elements themselves. If the scenario described in language lacks this, the scenario would remain just as an idea or a flash of thought which may not lead to discussions and collaboration with other people. We hope that the readers of this paper understand the necessity of the scenario better. Revisions were made throughout the paper based on this thought.

Consortium style study on the development of highly reliable photovoltaic modules and acceleration test methods

— Management of the "Consortium Study on Fabrication and Characterization of Solar Cell Modules with Long Life and High Reliability" —

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[Translation from *Synthesiology*, Vol.9, No.1, p.39-50 (2016)]

The "Consortium Study on Fabrication and Characterization of Solar Cell Modules with Long Life and High Reliability" was established by the National Institute of Advanced Industrial Science and Technology. The consortium had over 90 participating organizations, which were mostly module-material manufacturers. The purpose of the consortium was to improve reliability and lifetime of photovoltaic modules, and to develop acceleration test methods for accurate assessment of module lifetime. This paper details the establishment procedures and management policies of the consortium, with particular focus on resolving competing interests among the participants, as viewed from the perspective of the secretariat.

Keywords : Photovoltaic module, reliability, consortium, material manufacturer, human resource cultivation

1 Background of the establishment of the consortium

To reduce the cost of photovoltaic power generation, it is essential to increase the generated power during a lifespan through increased reliability and lifetime in addition to high efficiency and reduced manufacturing costs. The reliability and lifetime of the photovoltaic module are determined by the materials of the module including electrodes, interconnector ribbons, back sheets, encapsulants, sealing materials, potting materials, and others. Figure 1 shows the cross-section structure of the photovoltaic module. The interconnector ribbons play the role of soldering, and alternately connect the electrodes on the surface of the photovoltaic cells to the ones on the back. The back sheets protect the module against moisture ingress, and also maintain the electrical insulation and mechanical strength. The encapsulants fix the cells to prevent breakage. The sealing and potting materials protect the module from moisture ingress, just like the back sheets. On the other hand, as indicated in the text inside the box of Fig. 1, when the photovoltaic module is exposed outside for a long time, degradation of such materials occurs and may cause decreased power generation. Therefore, to increase the reliability and lifetime of photovoltaic modules, R&D is necessary in various phases from the materials development to prevent degradation to the assembly of modules, by conglomerating the findings of the photovoltaic cell manufacturers and the chemical and material companies that manufacture the module materials, along with the wide-ranging knowledge of physics, chemistry, electrical and electronic engineering, material science, and others. Therefore, the Research Center for Photovoltaics (this research unit changed its name to Research Center for Photovoltaic Technologies, and then changed its name back to Research Center for Photovoltaics) at the National Institute of Advanced Industrial Science and Technology (hereinafter will be called AIST) established a consortium mainly composed of the chemical and material manufacturers that were involved or were planning to enter into the photovoltaic industry. The plan was to promote R&D through close collaboration with the photovoltaic companies, and preparations were started at the Research Center from the latter half of fiscal year (FY) 2008. In 2008, when the consortium was planned, there was no university or public research institute that could engage in trial production and evaluation of photovoltaic modules in Japan, and verification of effectiveness for the module materials could only be accomplished by sending personnel or materials to the Fraunhofer Institute for Solar Energy Systems (Fh-G ISE) in Germany or the Energy research Centre of the Netherlands (ECN). Therefore, there were demands from the chemical and material manufacturers to set up a trial production and evaluation line in Japan. Of course, tests could be done at the Japanese photovoltaic companies, but in many cases, the conditions were not favorable for the chemical and material manufacturers, because the photovoltaic companies

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would not readily accept testing of new materials, would not disclose the results even if the testing was done, and partnership would not be possible with any other company if good results were obtained. Another background was that the research of photovoltaics at universities and public research institutes focused solely on cell research and study on modules was hardly done. AIST intended to academically organize as scientific findings the know-how of module reliability that the photovoltaic companies kept to themselves.

The consortium members were widely sought by open invitation, utilizing the example of the Flexible Solar Cell Substrates Consortium[1] conducted previously at the Research Center for Photovoltaics. The briefing session for the open invitation was held in Tokyo on February 2, 2009, and 168 participants were obtained. Another session was held in Fukuoka on February 17, 2009, and 117 participants were gathered. The reason for holding a session in Fukuoka was because a trial production and evaluation line for photovoltaic modules was due to commence operation in October 2010 at AIST Kyushu, and the plan was to use this facility as part of the research. We decided to hold individual interviews later with the participants that showed interest in establishing the consortium at the briefing. The 101 candidate consortium participants with whom we conducted interviews were convened, and a meeting for preparation of establishment was held in Tokyo on May 28, 2009. At the preparation meeting, we explained the principles and management policies of the consortium, exchanged opinions with all the candidates, and a social gathering was organized. On July 9, 2009, the second preparation meeting was held at Tsukuba, and 90 members belonging to the participating organizations that officially decided to participate in the consortium were convened. The consortium was named "Consortium Study on Fabrication and Characterization of Solar Cell Modules with Long Life and High Reliability (hereinafter, will be called the Consortium)," and there were 31 participating organizations (private companies), one collaborating organization (Photovoltaic Power Generation Technology Research Association, hereinafter, will be called PVTEC), and nine cooperating organizations. It was formally established on October 1, 2009 (with additional participation after the start, there were 33 private companies as participating organizations and 10 cooperating organizations in Consortium I in the end).

On October 21, 2009, the opening ceremony was held in Tokyo with Tamotsu Nomakuchi, President (at the time), AIST. Also attending were: Masanori Suzuki, Director-General (at the time), Industrial Science and Technology Policy and Environment Bureau, Ministry of Economy, Trade and Industry; Fumio Ueda, Executive Director, New Energy and Industrial Technology Development Organization; and Yukinori Kuwano, President (at the time), PVTEC.

The membership fee (paid to a joint research fund) of a participating organization was five million yen per fiscal year. The participating organization was required to dispatch one or more joint researchers to AIST, but they were not obliged to be constantly present, and flexibility was given to the dispatching of the researchers where they could visit AIST occasionally to conduct experiments depending on the progress of the research. It was determined that the constant stationing of researchers was difficult for the participating organizations. Moreover, there was a limitation on the AIST staff and research apparatuses, and it was not realistic for all

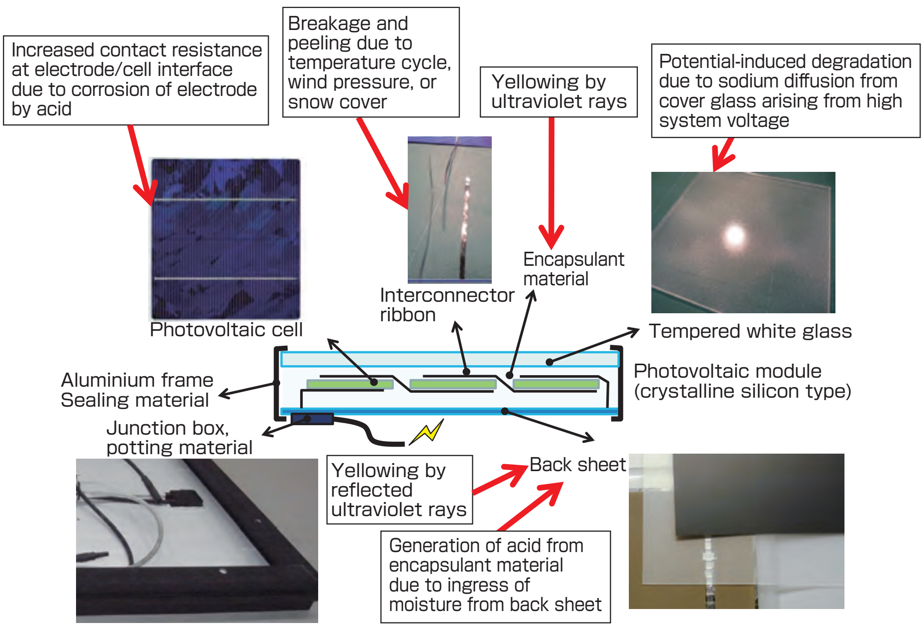

Fig. 1 Cross-sectional structure of photovoltaic modules
Text in the box shows the degradation factors that arise from module materials.

dispatched researchers of the 31 companies to be present at AIST to conduct experiments every day. For the reliability of photovoltaic modules, there was an agreement to engage in R&D under the strong collaboration with PVTEC before the establishment of the Consortium. Therefore, PVTEC was positioned as the collaborating organization, and becoming a member of PVTEC was set as a requirement for the participating organizations of the Consortium. Also, cooperating members were defined as those who would be requested to cooperate in advancing the Consortium research through provision of various findings concerning photovoltaic modules and through provision of materials, apparatuses, and analysis methods, although they would not be engaging directly in research. While the cooperating organizations were not required to pay to the joint research fund, they were asked to dispatch researchers when needed.

The content described in this paper will mainly concern the establishment and the management of the Consortium. The specific research results of the Consortium would be limited to the ones described in Chapter 6, and for full research results, please refer to the Reports[2]-[4] and the published papers listed in them, distributed at the three open report meetings that were held during the Consortium period.

2 Principles and management policies of the Consortium

The most important point of a consortium is to present the principles and conduct management based on the principles without going off course. The basic principle of this Consortium was to conduct R&D using the technological platform provided by AIST, to greatly improve the reliability and lifetime of photovoltaic modules, and to create unique technologies for dramatic cost reduction. Based on this principle, we encouraged open innovation by the participating organizations of the Consortium. The specific management policies were that the research results obtained in the Consortium would be, in principle, disclosed, and publications as papers and presentations at academic conferences were prioritized over patent application. As mentioned earlier, considering the fact that not much academic investigation had been done for the module technology and module reliability, we decided to devote ourselves to fundamental research for the purpose of obtaining academic and systematic research data, for the research of A Members of Consortium II that will be explained in Chapter 4. To realize such policies, we decided to take strict stance against participating organizations bringing in profit interests into the Consortium.

Based on the above principles and management policies, we created a joint research contract and management guidelines. This was done not solely by AIST, but volunteers joined from the Consortium members, and discussions were held about once in two weeks by the people of the following groups: Collaboration Promotion Department, AIST (currently, Collaboration Promotion and International Affairs Division, Research and Innovation Promotion Headquarters), Intellectual Property Department, AIST (currently, Intellectual Property and Standardization Promotion Division, Research and Innovation Promotion Headquarters), as well as the researchers of the Research Center for Photovoltaics, AIST; and participating organizations. It is thought that this involvement of the participating organizations as volunteers in creating the joint research contract and management guidelines played an important role in nurturing trust among the participating organizations and AIST. Majority of the volunteers from the participating organizations that were involved in the creation attended the executive meetings held about once a month as officers of the management committee after the establishment of the Consortium, to solve various obstacles with AIST staff, particularly during the confusion at the start of the Consortium. In the management guideline, various committees that configured the Consortium, including the management committee, the technical advisory committee, and the invention review committee were defined. Particularly, valuable advice was given on the direction of research based on the Consortium principles, from the technical advisory committee composed of about 10 members, and this played an essential role in managing the very start of the Consortium. The members of the technical advisory committee were selected from the members of photovoltaic companies, apparatus companies, material manufacturers, universities, and AIST. By having the technical findings accumulated by the photovoltaic companies reflected in the research of the Consortium participants that were mainly composed of material manufacturers, we ensured that the material manufacturers could engage in research from multi-faceted perspectives. The management guideline is presented in entirety in Reference [4].

3 Management of Consortium I

Consortium I was established under a contract period of one and half years from October 1, 2009 to March 31, 2011. The management of the Consortium immediately after launch was extremely difficult. There were several reasons, but the ones arising from AIST were that AIST hardly had any experience in module research, was not able to take the leading role for the participating organizations, and fumbled along in carrying out the daily research activities. Also, many AIST staff members joined the Consortium immediately before the establishment, and the communication among them was insufficient. On the other hand, the issues of the participating organizations were the different degrees of interest among the organizations. There were members who were already doing business in the photovoltaic industry, and others who joined with almost no knowledge but hoped to seek opportunities in the emerging photovoltaic industry. The latter members tended to sit and wait for AIST to come up with a solution when the research hit a wall. Joint research must be done by all parties working to arrive at a solution, and our inability to emphasize this policy at the start of the Consortium is a point of reflection.

For the inventions in the Consortium, not once did we have differences of opinion among the Consortium members that required convening the invention review committee, as there were only a few inventions as will be explained later. In the Consortium where all the participating organizations signed the same contract and were on equal terms, it seemed that there was a consciousness that the organization should take the same steps as other participants, and the trouble pertaining to invention was less likely to occur than in a one-to-one contract. On the other hand, there were differences in interest due to cultures and strategies of the participating organizations, such as in the publications of results as papers and presentations at academic conferences, and it could not be denied that some participating organizations were more passive than others.

After about half a year from the launch of Consortium I, some researchers became enthusiastic in becoming involved in the Consortium activities as a whole. This resulted in the search for joint research topics, where topics that might lead to issues solved for the entire industry although it might not lead to short-term profit of the participating organizations were collected, and the volunteers of the Consortium jointly engaged to study the topics. There were three specific topics: 1) survey of the influence of properties of the module encapsulant materials on the module performance, 2) actual state of failures and degradation in the photovoltaic modules, and 3) development of novel testing methods for modules. The AIST researchers took the lead to research the topics. For the research results, after exchanging opinions at the technical advisory committee, Topic 2) for which the research could be started in a relatively short period of time was started immediately, and for Topics 1) and 3), it was decided that research would be started in Consortium II. 11 researchers participated in Topic 2), and research results were presented at a total of 12 meetings to further the discussion. As can be seen from the fact that the results were reported in detail, covering over one-third of the 327 pages of Consortium I Report, this search for joint research topics played a major role in solidifying the Consortium. It should also be noted that this search was proposed by the participating organizations.

4 Establishment of Consortium II

As mentioned in Chapter 3, three joint research topics were found, including the topics that were not addressed in Consortium I, and this allowed the authors to mold the concept for Consortium II, a continuation of I. This meant dividing the Consortium members into A Members who would mainly engage in the above topics that were fundamental research topics where the results could be readily shared by all participating organizations, and B Members who would verify the effectiveness of the module materials that the companies developed on their own.

Although the activities of A Members would not generate short-term profit for the companies, they might generate fundamental results pertaining to the reliability of photovoltaic modules, and might contribute to both the academia and industry. Basically, A Members would engage in the three core research that carried over from the three topics set in the search for joint research topics of Consortium I. Table 1 shows the research of three core topics in which the A Members engaged. Since the A Member's research would contribute to the entire photovoltaic industry, the fee of the A Member was set at 2 million yen/FY that was lower than the fee for B Members. To guarantee the continuous research activity throughout the Consortium, no new members would be accepted during the three-year Consortium II period for the A Members, and no withdrawals would be accepted. Special Member category was set up for A Members which exempted them from membership fees, and removed the requirement that they had to be members of PVTEC. There were the following reasons for doing so. First, by exempting the module manufacturers and related organizations from the membership fee as Special Members, we expected such organizations to participate actively in the Consortium. In Consortium I, it was indicated that the Consortium members who were mainly material manufacturers and photovoltaic manufacturers did not have a strong relationship, and the objective was to solve this issue. Second, in order to incorporate the academic findings into A Members that engage in fundamental research, we hoped to gain active involvement of universities and others by exempting the membership fee. By setting up the special membership system, we opened a way for some photovoltaic manufacturers and universities that were not members of PVTEC to participate as A Members.

On the other hand, the membership fee of B Members was set at a basic 3 million yen/FY to which the amount corresponding to the number of trial production would be added (specific fee). For Consortium I, an equal membership fee of 5 million yen/FY was set for all participating organizations, but the specific fee was set so the fees of the B Members that engaged in average activities would be about equal to the fee of Consortium I. We mentioned that there were differences in interest among the members in Consortium I, and it seemed that the differences were generated from the differences in the purpose of participation and expectation for the Consortium

Table 1. Contents of the three core research topics in which the A Members engaged

Topic No.	Topic title	Outline	R&D points
1	Detailed survey of long-term exposed modules	To analyze the occurrence of module failure/trouble and the degradation of power generation performance, through the destructive analysis of modules that have been exposed for a long period of time or through the survey of installed modules.	・Carefully survey and analyze the degradation and failure factors at a microscopic level through destructive test of long-term exposed modules. ・Collect case studies of failures/troubles of modules installed in megawatt-scale photovoltaic plants.
2	Clarification of degradation factors using the test modules	To clarify the degradation factors of module performance by developing a test module that allows visualization of the area of degradation, a test module that intentionally includes the degradation factor, and sensing technology.	・Develop a test module that allows visualization of the area of degradation, and a test module that intentionally includes the degradation factor. ・Develop sensing technology that enables monitoring the degradation status. ・Clarify the required properties of the module materials and structures through the evaluation of degradation factors.
3	Development of novel reliability test methods	To develop novel reliability test methods, based on the results of Topics 1 and 2.	・Develop novel reliability test methods such as an acceleration test that combines major degradation factors and shortening of the test time by highly accelerated tests. ・Develop novel reliability testing apparatuses. ・Reflect the obtained results in standards.

of individual participating organizations. These differences could not be resolved completely in Consortium I, but roughly separating the research objectives to fundamental research for A Members and short-term R&D for B Members contributed greatly in resolving the differences in interest. Also, it seemed that the membership fee based on a specific fee system helped resolve the differences in interest and the feeling of inequality.

Moreover, we set up the C Membership where the members could learn about the findings in photovoltaic fields through participating in technological exchange sessions held four times a year, in hopes that such findings might help development in their companies and might encourage participation as B Members. In the technological exchange sessions, lectures were given by external experts, and the results of A Members were presented before they became officially public. On average about 100 people participated in these technological exchange sessions, and they functioned as a place of communication for all Consortium members including the A, B, and C Members as well as the cooperating organizations and technical advisory committee members. The membership fee for C Members was set at 500 thousand yen/FY, and one could participate readily due to the lowered hurdle of the membership fee. When the universities and public research institutes participated as C Members, the membership fee was waived in hopes of widening the horizon of this field. While the C Members participated in the Consortium activities, they were less likely to create intellectual properties compared to the research activities of the A and B Members, and various discussions were held on the pros and cons of concluding joint research contracts equivalent to the ones for A and B Members. As a result, both the contract relationship and smooth participation environment were maintained by concluding a joint research contract where the items about intellectual property were greatly reduced, recognizing that there will be no creation of intellectual property. Similarly to Consortium I, a system was established for the cooperating organizations that contribute to the acceleration of Consortium R&D, through provisions of materials, apparatuses, and analysis methods, as well as provision of various findings on photovoltaic modules. The main roles and participating conditions of the A, B, and C Members are shown in Table 2, including comparison with Consortium I.

For the establishment of Consortium II, a planning committee composed of volunteers of Consortium I members and exterior experts was established to bring in wide-ranging expert opinions. Three focused exchanges of opinions were held in a relatively short period of time, on August 31, October 5, and October 28, 2010. The framework and principles of Consortium II was formed based on the above draft by the authors while incorporating the expert opinions, and these were reflected in the application guideline. The briefing session of Consortium II was held in Tokyo on December 16, 2010 and in Tosu, Saga Prefecture on December 17, 2010, and 158 and 76 people attended, respectively. Ultimately, the number of participants surpassed that of Consortium I, and there were 19 participating organizations as A Members, 20 as B Members, 27 as C Members, and 15 cooperating organizations (at the time of establishment). Consortium II was established on April 1, 2011.

Table 2. Comparison of the main role and the participation conditions for A, B, and C Members for the organizations of Consortiums I and II

	Consortium I participating organizations	Consortium II A Members	Consortium II B Members	Consortium II C Members
Main role in the Consortium	· Basically engage individually in research for the topic and goal set by each participating organization, but the research results will be shared at the monthly research meetings.	· Several A Members and AIST form groups and engage jointly in the core topic research. A group is formed for each topic, but information is shared among the groups. · After the members are set, division of roles is determined based on the consultation with AIST. · Special Members are defined as the module manufacturing companies, organizations working on standardization, universities, and public research institutes. · Dispatched researcher will engage in the core topic research at AIST, at engagement ratio (or more) decided after consultation, but the participation in the research topic as B Member will be accepted if additional fee is paid. · There will be no rules for engagement ratio for the Special Members.	· Conduct trial production and evaluation of module using the materials of the proposing party under individual joint research contract with AIST. · Joint research is conducted in collaboration with other B Members under mediation by AIST, as needed. · If requested, AIST mediates the collaboration with module companies.	· Participate in technological exchange sessions (closed participation; results of A and B Members before publication and disclosure information are provided).
Basic participation fee	· 5 million yen/FY · Multiple fiscal year contract from 2009 to 2010	· 2 million yen/FY (free for Special Member) · Multiple fiscal year contract from 2011 to 2013. · Basic additional participation fee is 1 million yen/FY when engaging in research topic as B Member (Special Member must pay 3 million yen/FY).	· 3 million yen/FY · Single fiscal year contract	· 500 thousand yen/FY (free for universities and public research institutes) · Single fiscal year contract
Fees for trial production and evaluation	· Included in basic participation fee	· Included in basic participation fee when engaging in research topic as A Member. · Specific fee is set considering the content of trial production and evaluation (size, number, occupancy time, etc.) when engaging in research topic as B Member.	· Specific fee is set in accordance to the content of trial production and evaluation (size, number, occupancy time, etc.).	· Does not apply
Type of contract with AIST	· Conclude joint research contract. Basic participation fee and per capita costs are paid to AIST joint research fund, and the term and method of payment shall be set in the joint research contract.	· Conclude joint research contract. Basic participation fee, additional fee, and per capita costs are paid to AIST joint research fund, and the term and method of payment shall be set in the joint research contract.	· Conclude joint research contract. Basic participation fee, additional fee, and per capita costs are paid to AIST joint research fund, and the term and method of payment shall be set in the joint research contract.	· Conclude joint research contract. Basic participation fee is paid to AIST joint research fund, and the term and method of payment shall be set in the joint research contract.
PVTEC membership	· Must apply for PVTEC membership.	· Must apply for PVTEC membership (Special Member does not need to do so).	· Must apply for PVTEC membership.	· Do not have to apply for PVTEC membership.

Table 3. Members that participated in the Consortium

Membership category	Name of organizations
Consortium I participating organizations	Asahi Glass Co., Ltd.; Asahi Kasei Chemicals Corporation; C. I. Kasei Co., Ltd.; Dai Nippon Printing Co., Ltd.; Daicel Chemical Industries, Ltd. (currently, Daicel Corporation); Daiken Chemical Co., Ltd.; Daikin Industries, Ltd.; Denki Kagaku Kogyo K. K. (currently, Denka Company Limited); DIC Corporation; Du Pont-Mitsui Polychemicals Co., Ltd.; DuPont K. K.; ESPEC Corp.; Fujifilm Corporation; Fujimori Kogyo Co., Ltd.; Hitachi Chemical Co., Ltd.; Kaneka Corporation; Kuraray Co., Ltd.; LINTEC Corporation; Mitsubishi Plastics, Inc.; Mitsubishi Rayon Co., Ltd.; Mitsui Chemicals, Inc.; Nissan Chemical Industries, Ltd.; Nitto Denko Corporation; Okura Industrial Co., Ltd.; Sekisui Chemical Co., Ltd.; Sony Chemical & Information Device Corporation (currently, Dexerials Corporation); ThreeBond Co., Ltd.; Toppan Printing Co., Ltd.; Toray Engineering Co., Ltd.; Toray Industries, Inc.; Toyo Aluminium K. K.; Toyobo Co., Ltd.; ULVAC, Inc.
Consortium I collaborating organization	Photovoltaic Power Generation Technology Research Association
Consortium I cooperating organizations	Dow Corning Toray Co., Ltd.; Hanwha Q CELLS Japan Co., Ltd.; Japan Electrical Safety and Environment Technology Laboratories; Kikusui Electronics Corporation; Kobelco Research Institute, Inc.; Lasertec Corporation; NPC Inc.; SAES Getters S.p.A.; Teijin DuPont Films Japan Limited.; Yocasol Inc. (currently, Japan Solar Factory Co., Ltd.)
Consortium I organizations selected for technical advisory committee	ESPEC Corp.; Gifu University; Kaneka Corporation; Mitsubishi Heavy Industries, Ltd.; National Institute of Advanced Industrial Science and Technology; Sharp Corporation; Toray Industries, Inc.
Consortium II A Members	Choshu Industry Co., Ltd.; Dai Nippon Printing Co., Ltd.; Daikin Industries, Ltd.; DuPont K. K.; ESPEC Corp.; Hitachi Chemical Co., Ltd.; Industrial Research Institute of Ishikawa; Japan Electrical Safety and Environment Technology Laboratories; Kaneka Corporation; Mitsubishi Electric Corporation; Photovoltaic Power Generation Technology Research Association; Ritsumeikan University; Teijin DuPont Films Japan Limited.; The Japan Electrical Manufacturers' Association; Tokyo Electron Limited.; Toppan Printing Co., Ltd.; Toyobo Co., Ltd.; ULVAC, Inc.; Yocasol Inc. (currently, Japan Solar Factory Co., Ltd.)
Consortium II B Members	Asahi Kasei Corp.; Dai Nippon Printing Co., Ltd.; Daikin Industries, Ltd.; Denki Kagaku Kogyo K. K. (currently, Denka Company Limited.); DIC Corporation; Du Pont-Mitsui Polychemicals Co., Ltd.; Fujifilm Corporation; Hitachi Chemical Co., Ltd.; Kuraray Co., Ltd.; Kyodo Printing Co., Ltd.; LINTEC Corporation; Nissan Chemical Industries, Ltd.; Nitto Denko Corporation; Okura Industrial Co., Ltd.; Shin-Etsu Chemical Co., Ltd.; Sony Chemical & Information Device Corporation (currently, Dexerials Corporation); Sumitomo Seika Chemicals Co., Ltd.; TANAKA HOLDINGS Co., Ltd.; Toppan Printing Co., Ltd.; Toray Engineering Co., Ltd.; Toray Industries, Inc.; Toshiba Mitsubishi-Electric Industrial Systems Corporation; Toyo Aluminium K. K.; Toyobo Co., Ltd.
Consortium II C Members	ADC Corporation; Bridgestone Corporation; C. I. Kasei Co., Ltd.; Daiken Chemical Sales & Mfg. Co., Ltd.; Dexerials Corporation; DIC Corporation; Fujikura Ltd.; IHI Corporation; IMV Corporation; Industrial Technology Center of SAGA; ITES Co., Ltd.; Iwasaki Electric Co., Ltd.; Kagoshima Prefectural Institute of Industrial Technology; Kanagawa Academy of Science and Technology; Kanazawa Institute of Technology; KEIWA Inc.; Kitakyushu Foundation for the Advancement of Industry, Science and Technology; Kumamoto Industrial Research Institute (Kumamoto Organic Electronics Collaboration Council); Kuraray Co., Ltd.; Kyushu Electric Power Co., Inc.; Mitsubishi Rayon Co., Ltd.; Mitsui Chemicals, Inc.; Murata Manufacturing Co., Ltd.; NEOMAX Materials, Co., Ltd.; Nisshinbo Holdings Inc.; ORIX Corporation; Saga Ceramics Research Laboratory; Saga University; SAN-EI ELECTRIC Co., Ltd.; SANVIC Inc.; Sekisui Chemical Co., Ltd.; Senju Metal Industry Co., Ltd.; Sumitomo Chemical Co., Ltd.; Togami Electric Mfg. Co., Ltd.; TOKYO OHKA KOGYO CO., LTD.; TOYO Corporation; Ushio Inc.
Consortium II cooperating organizations	Dow Corning Toray Co., Ltd.; Fuji Electric Co., Ltd.; Hanwha Q CELLS Japan Co., Ltd.; ITES Co., Ltd.; JFE Techno-Research Corporation; Kikusui Electronics Corporation; Kobelco Research Institute, Inc.; Lasertec Corporation; NEOMAX Materials Co., Ltd.; NISHIKAWA KEISOKU Co., LTD.; NPC Inc.; ORIX Rentec Corporation; SAES Getters S.p.A.; Shimadzu Corporation; Toray Research Center, Inc.
Consortium II organizations selected for technical advisory committee	ESPEC Corp.; Fuji Electric Co., Ltd.; Honda Soltec Co., Ltd.; Kaneka Corporation; KYOCERA Corporation; Mitsubishi Heavy Industries, Ltd.; National Institute of Advanced Industrial Science and Technology; Osaka University; SANYO Electric Co., Ltd.; Sharp Corporation; Solar Frontier K. K.; Toray Industries, Inc.

Table 3 shows the list of the members for Consortiums I and II.

5 Management of Consortium II

Consortium II was established with a contract period from April 1, 2011 to March 31, 2014. Immediately before the start of Consortium II, the Great East Japan Earthquake occurred on March 11, 2011, and the experimental facilities and infrastructures of AIST Tsukuba were greatly damaged and research could not be conducted for several months. There were companies among the participants of Consortium I with facilities in the disaster area, and recovery became the priority. Due to such circumstances, half-year extension was discussed for Consortium I. The extension was officially decided on April 12, 2011 at Consortium I and II joint emergency management committee meeting held at AIST Kansai to avoid the aftershocks of the earthquake. Therefore, the first half-year of Consortium II was spent trying to restore the laboratories, and there was confusion as research was carried out by both Consortium I and II members. However, since there were also experimental facilities in AIST Kyushu besides AIST Tsukuba, the effect of the disaster on the research was alleviated. This could be evaluated positively as a lesson learned in risk management.

In Consortium II, AIST was uninvolved in the research content of the B Members that individually conducted effectiveness verification of the materials developed on their own. It was thought that the B Members could readily engage in research if left on their initiative, and the B Members themselves planned and executed research without intervention from AIST, and AIST simply provided materials, apparatuses, analysis methods, and other help based on the research situation. In contrast, AIST took lead in the research done by the A Members, and research meetings were held all afternoon about once a month, where AIST gave detailed advice on data interpretation as well as direction of research. However, over time, the B Members started to voice desire for regular research meetings, and they were held at a frequency of once in several months. This was proof that the Consortium members started to recognize the importance of discussion at such meetings rather than worry about data getting disclosed to competing companies. It seemed we have come a long way from the start of Consortium I. The technical advisory committee was not held in Consortium II, but its importance was recognized, more so than in Consortium I, as the technical advisory members attended the research meetings of the aforementioned A and B Members, and valuable comments were given on the direction of research. The technical advisory members were mostly researchers of the photovoltaic manufacturers, and active discussions were held on some areas that were kept as know-how. We believe the collaboration in the true sense progressed among the chemical, material, and photovoltaic manufacturers, which was one of the objectives of the Consortium.

6 Publication and intellectual property

Based on the Consortium principle that the research results will be disclosed, several presentations were made as papers and given at academic conferences and exhibitions. There were only 42 presentations in Consortium I since it was the start-up period, but there were 152 presentations (at the completion) of Consortium II. There were cases where the comments received at the academic conferences or exhibitions became hints in advancing the research. Moreover, we were able to witness young researchers dispatched from participating organizations grow as researchers through writing papers in English or giving presentations at international conferences. We feel major contributions were made in human resource training.

The representative research results obtained in this Consortium include the following.

Results of Consortium I

- Survey of modules exposed outdoors
  Upon surveying and analyzing 158 modules that were exposed outdoors for a long time, it was found that sodium is deposited at the interface between the encapsulant and the cell surface where peeling occurs,[2][5] and that the interconnector failures occur mainly on the backside of the cell surface.[2][6]
- Development of a high-acceleration test method
  It was found that accelerating the rate of temperature increase/decrease during the thermal-cycle test affects the acceleration of physical and mechanical degradation of the module, and that the *in situ* observation of impedance during the test is effective in capturing the signs of degradation.[7]

Results of Consortium II

- Relationship between long-term outdoor exposure and the acceleration test
  The relationship of long-term outdoor exposure and damp-heat tests that was a matter of concern for a long time was clarified using the amount of acetic acid in the module as an index. It was found that 30 years of outdoor exposure in Japan is equal to 4,000 hours of a damp-heat test at temperature of 85 ºC and relative humidity of 85 %.[4][8] This result was part of the Best Paper Award, 6th World Conference on Photovoltaic Energy Conversion.
- A combined test of salt-mist spray and potential-induced degradation
  Although the photovoltaic properties of the module is not degraded by salt-mist spray only, test results showed that the potential-induced degradation is promoted by prior salt-mist spraying. This supported the phenomenon where the potential-induced degradation seems likely to occur in the coastal area.[4][9]
- Verification of the effectiveness of a new encapsulant material
  By using polyvinyl butyral as an encapsulant material, a thin film silicon photovoltaic module with no degradation after 15,000 hours of a damp-heat test, which is about 15 times the test time set by the international standard, was successfully developed.[4][10]
- Verification of effectiveness of a new surface cover material
  By developing a module that used an acrylic resin material for the cover material, it was possible to reduce the weight of the module to half the conventional one. Moreover, it was confirmed that it passes the fire test as well as various reliability tests. It also proved to have excellent resistance against potential-induced degradation.[4][11]

For patents, there were only two patents throughout Consortiums I and II.[12][13] This was the result of upholding the policy that the technologies valued by the participating organizations such as the manufacturing method of materials or others did not have to be disclosed in the Consortium, and devoted effort was placed on research in the noncompeting fields. On the other hand, we set a rule that the patents created in the Consortium should not prevent the exploitations by other participating organizations of the Consortium. Therefore, if the research result of the Consortium was included in one of the exploitations, the exploitations by other organizations would not be prevented by the patent, and these might include the claims of a manufacturing method for which the patent holding company would never allow the competing companies to use. For this point, rather than the whole patent permitting the exploitations by other Consortium participating organizations, we attempted resolution by revising the joint research contract and the management guideline to limit the range whereby the exploitations by other organizations would be permitted by the claims based on the research results of the Consortium. On the other hand, the legal and intellectual property divisions of the participating organizations have questioned the interpretation of the contract on whether one-to-one contract between AIST and the participating organization would be enforceable against the exploitations of other organizations. Which style of contract is better for the Consortium remains as a future issue.

7 Consortium secretariat

Since the Consortium is composed of several participating organizations, strict non-disclosure among the participating organizations would be required. The data were under uniform management by the Consortium secretariat, the data obtained from the participating organizations were clearly demarcated and stored, and the access privileges were limited. On the other hand, if the confidentiality of the participating organizations were thoroughly enforced, the unity of the Consortium would be lost. It was extremely difficult to maintain the balance, but through the trust nurtured as the research progressed, there were no major troubles among the participating organizations, and we were able to maintain a unified activity as a consortium. Of course, the activities of A Members were limited to noncompeting fields, and for the activities of B Members, the information that the participating organization wished to keep secret did not have to be brought to the Consortium. This had great effect on the unified management of the Consortium, but ultimately the atmosphere of nurturing trust between AIST and the participating organizations and amongst themselves was important, and such environment could not be obtained simply by setting perfect rules. Of course, the trust in AIST was nurtured as the research results were obtained smoothly. Needless to say, the trust among the participating organizations grew because it was a consortium managed under AIST.

In a consortium in which several organizations participated, difficulties were expected in adjusting the schedule because many of the apparatuses used in research would be shared and the machine time would be limited. The software with a schedule management function that could be accessed by the Consortium members was introduced. However, the presence of a highly talented secretary was crucial in the smooth flow of the Consortium secretariat work, including schedule management of visiting members, scheduling of various meetings on various subjects, making a contract with the participating organizations, budget management including the procurement of items used in research, reservation of venues for the meetings, various notifications to external participants, and management of the actual meetings. In this sense, the Consortium management was successful because we were blessed with an excellent secretary for various administrative affairs.

8 Succeeding consortium

The Consortium Study on Fabrication and Characterization of Solar Cell Modules with Long Life and High Reliability started as Consortium I on October 1, 2009, and after four and half years of activities, it ended successfully on March 31, 2014. During this period, the situation surrounding photovoltaics changed greatly. At the start of the Consortium, as the semiconductor and liquid crystal industries faced hardships, many material manufacturers shifted to photovoltaics as the next pillar of profit. However, the photovoltaic industry in Japan lost the world market share at a faster pace than semiconductors and displays, and currently, the cell and module barely reach 10 % share. Due to such changes in the situation, even the companies that manufacture and sell the photovoltaic module materials currently are struggling to maintain their footing, and there are hardly any new material manufacturers that are willing to enter this field. This situation is clearly reflected in the budget for consortium management and the number of participating organizations. At the latter half of Consortium II, one-third of the B Members decided not to continue, but the number of participating organizations did not drop dramatically due to the binding of contract during the Consortium period. However, as shown in Fig. 2, after the completion of Consortium II, the number of participating organizations decreased dramatically and the amount of budget was also drastically reduced. There were many reasons given for discontinued participation in the Consortium: the facilities for trial production and evaluation of photovoltaic modules were set up in the company; a path for R&D had been cleared in the company; the R&D for photovoltaic module was terminated after review of the business plans; and others. These are not unrelated to the fact that the Japanese photovoltaic industry is losing shares in the market. Therefore, it was impossible to establish a new, large-scale consortium. Instead, we established a small-scale, succeeding consortium with three private companies that participated in Consortium II.

The succeeding consortium continued the research of the A Members of Consortium II, and focused on the fundamental research limited to the clarification of degradation phenomena in the photovoltaic modules and test methods, and aimed at participating in the projects with a government grant. As a result of continuing such activities, the following eight organizations submitted a joint proposal: DuPont K.K.

and Toray Industries, Inc., that were continuing joint research in the succeeding consortium; Industrial Research Institute of Ishikawa, Gifu University, Japan Advanced Institute of Science and Technology, and Tokyo University of Agriculture and Technology that were engaging individually in joint research; Tokyo University of Science (a new member); and AIST. The proposal was selected as contract research entitled “Development of high performance and reliable PV modules to reduce levelized cost of energy / Development of common fundamental technologies (Reliability evaluation technology of PV systems) / Prediction of lifetime and development of test methods for photovoltaic modules” of the New Energy and Industrial Technology Development Organization (NEDO). This enabled the continuation of research for about five years to February 2020, for the fundamental technologies such as the clarification of degradation mechanism and a test method that enables lifetime prediction of photovoltaic modules. An environment is being prepared for an academically systematized study based on scientific findings related to module reliability. This has been the authors’ desire since the establishment of the Consortium. Although the general direction is to promote joint research with private companies utilizing the results of the projects run by government grants, collaboration with exterior organizations cannot always be explained by a simple linear model, and peripheral situations must be considered. The story line presented here may become a model case where the project may return to a government-funded phase from joint research with private companies.

On the other hand, for the research carried out by the B Members of Consortium II, one-to-one joint research contracts were concluded rather than the consortium format. In the joint research with Shin-Etsu Chemical Co., Ltd., it was confirmed that the encapsulant material this company developed had remarkable effect on increasing reliability and that it was compatible with the current module fabrication apparatus, and a joint press release on this was published by Shin-Etsu Chemical Co., Ltd. and AIST on June 22, 2015.[14] Considerable time is necessary before the research comes into fruition, and this was a case that showed the importance of steady, continued joint research even after the completion of the consortium.

For the succeeding consortium, to ensure that the researchers could focus on yielding academic results without being tied to the interests of the dispatching companies, the following article was added to the contract: “It is understood that this joint research is a place to conduct scientific and technological discussion and to seek truth through research activities, and it is confirmed that conflict of interest among the parties entering the contract that may impede the execution of this joint research shall not be brought into the research.” For the one-to-one joint research, the following article was included to enable trial production of modules for companies other than the organizations currently entered into contract: “AIST may conduct similar joint research (meaning conducting experiments using the same facilities at the same place within AIST’s premises) with joint researchers other than the partner organization (entered in this contract), as long as such activities do not violate this contract, without prior or *ex post facto* notification to the partner organization.” Based on various experiences we obtained in Consortiums I and II, we believe it is necessary to conclude flexible contracts that allow maximum activation of the research for both AIST and the partner organization according to the

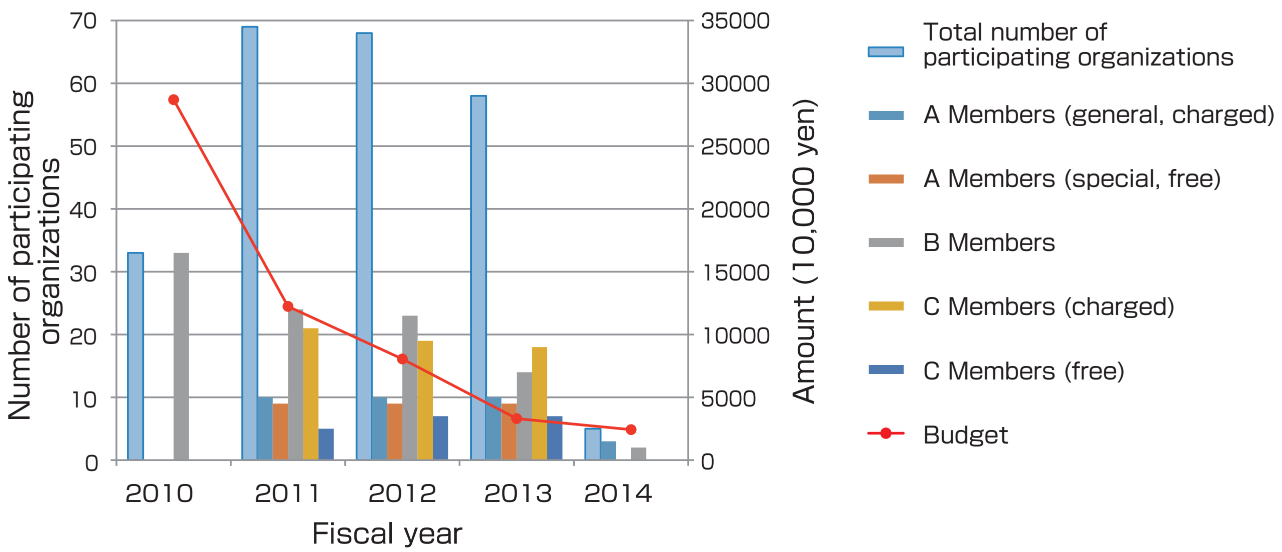

Fig. 2 Number of participating organizations in the Consortium and the transition in budget
For FY 2010, the number of participating organizations in Consortium I from the latter half of FY 2009 and the budget are shown. C Members (charged) were private companies, while C Members (free) were universities and public research institutes. For FY 2014, the participating organizations in the succeeding consortium were defined as A Members, and organizations with individual contracts were B Members.

situation.

The greatest objective of the Consortium was to engage in research of fundamental technology in noncompeting fields and academic deepening and systematization of the research results. In the future, we hope the results of the Consortium will be used in the development of application fields.

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Authors

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Leader, Strategic Industrialization Team, Research Center for Photovoltaics, AIST in 2005; Leader, Collaborative Research Team for Reliable Photovoltaic Modules in 2010; Leader, Collaborative Module-Reliability Research Team, Research Center for Photovoltaic Technologies in 2011; Leader, Module Reliability Research Team, and Deputy Director, Research Center for Photovoltaics in 2015. Also, Deputy Director, Renewable Energy Research Center in 2015. Collaborative Professor, Saitama University; and Visiting Professor, Japan Advanced Institute of Science and Technology. Received the Best Paper Award, 6th World Conference on Photovoltaic Energy Conversion in November 2014, for the research results obtained in the Consortium described in this article. As described in this paper, contributed to the general management of the Consortium, particularly on its management based on the principle of constructing an academically systematized study through fundamental research to increase reliability of photovoltaic modules and the development of the testing method. In this article, wrote Chapters 1~3, 5, and 7, and parts of Chapters 4, 6, and 8.

Nanako IGAWA

Born in 1982. Completed the master's course at the Graduate School of Public Policy, the University of Tokyo in 2007. Joined AIST in 2007. Worked at the Planning Headquarter; Personnel Office, Human Resource Department (Human Resource Division); Collaborative Research Support Office, Collaboration Promotion Division; Website and Publication Office, Public Relations Department; Public Relations Information Office, Planning Headquarter; to present. While at the Collaboration Promotion Division, worked on joint research contracts and management guidelines for new style consortiums, in which several competing companies joined, and contributed to their adjustment and organization. In this article, wrote parts of Chapters 4, 6, and 8.

Discussions with Reviewers

Overall comment

This is a descriptive article that shows that it is possible for a large number of companies to cooperate in the development of common fundamental technology through the establishment of a consortium. It presents the course by which the topics of the consortium were set based on the decision that both the construction of reliable trial manufacturing line and the establishment of reliability evaluation technology of photovoltaic modules would be valuable, because the reliability evaluation technology of academia and industry were scarce at that time. It also explains the process of obtaining the understanding of the participating companies for the consortium management policy. I believe this is a success story that will have a large ripple effect on other fields in the future.

It should be highly evaluated that for the reliability evaluation technology which is the core, the acceleration test method was established through research supported by scientific evidence to replace know-how and rule of thumb.

From the above points, it is determined that this article is appropriate for publication in *Synthesiology*.

1 Factors that led the Consortium to success

Comment (Akira Kageyama, Research Support Advisor, AIST)

As the factors that led the Consortiums I and II to success, you describe that you clearly defined the basic principles, considered the actual situation the industries were facing in creating the joint research agreement and management guideline to achieve the principles, and you carefully worked on the preliminary preparations to set rules pertaining to the handling of secret information and intellectual properties (Chapter 2). Also, in Chapter 7, you mention that the nurturing of trust amongst AIST and participating companies was extremely important. These are extremely useful to know. However, considering the composition of the article as a whole, I think you should state in Chapter 2 that various guidelines were set because you were conscious of nurturing trust. Of course, as you write in Chapter 7, a big factor is that the secretariat spent effort to respond fairly, swiftly, and appropriately, and there is no problem in emphasizing the nurturing of trust there.

Also, I think that the companies, when they first joined, had different expectations for the Consortium. Can you please offer more specific descriptions on how you managed to point the vectors of interest in the same direction?

Answer (Atsushi Masuda)

Thank you for your very accurate indication. The nurturing of trust between AIST and the participating organizations can be traced back to the fact that the joint research agreement and management guidelines were set through cooperative effort, and this point was added to Chapter 2.

For your second indication, it was not possible to point all vectors completely to one direction in Consortium I. What was useful in bundling the vectors was the categorization of members in Consortium II. I added the description in Chapter 4.

2 Topic setting and its effect

Question (Akira Yabe, NEDO Technology Strategy Center)

While there are several forms of successful open innovation, can you give specific explanation including the background of why you picked the research topics of common, fundamental, and cooperative fields such as lifetime prediction and degradation mechanism, and the test of materials that are characteristic to the companies, in the R&D for photovoltaics? Also, I think it is important to add what topics were taken to which level, and what manner of management was useful for achieving the level for topics addressed in the Consortium.

On the other hand, why didn't you address the issues that may become important in the future, such as the cost reduction by thinner crystalline silicon, or the cost reduction in balance of system other than the photovoltaic cell or module?

Answer (Atsushi Masuda)

Thank you for making precise indications. The research pertaining to reliability such as lifetime prediction and degradation mechanism of photovoltaic modules are fundamental studies, but these were not addressed actively in the academic world, and in reality, many were kept secret as know-how in the industry. In this Consortium, the research on module reliability came to light, and was promoted under the strong will of the authors who wished to contribute to the photovoltaic industry by systematizing the academic knowledge through research supported by scientific evidence. Moreover, at the time, there was demand from the industry to conduct verification tests for module reliability at public research institutes, and the Consortium was born from the matching way of thinking of the two parties.

The most important result of this Consortium was that we found the index that correlates the long-term outdoor exposure and the acceleration test. By obtaining the experimental fact that the 4,000 hours of damp-heat test was equivalent to 30 years of outdoor exposure in Japan, we set a guideline for lifetime prediction. I believe this is the result of consortium management based on the philosophy of conducting research backed by scientific evidence, for the module reliability that was traditionally dependent on know-how and rule of thumb. I added these points in the paper.

As you indicated, topics such as thinning of crystalline silicon and cost reduction in balance of system are important. However, the former is directly linked to the industry, the phase was different from what the authors had in mind, and the topic stepped into the domain of competition, and I thought it was difficult to establish a consortium for such a topic. For the latter, the recognition of its importance was lower compared to now for the whole industry, and there was lack of human resources at AIST.

3 Categorization of the members and technical advisory committee

Question (Akira Kageyama)

When shifting from Consortium I to II, you separated the A Members whose objectives were to deepen the fundamental technology and B Members whose objectives were to evaluate the company-developed materials by trial manufacturing. Why did you decide to make such foundational improvements or changes to the consortium management?

In a consortium that crosses over several industries (materials, apparatuses, and photovoltaic cells) as described in this article, total management that takes into consideration the vertical and horizontal relationships is extremely important. You write that setting of the technical advisory committee, which was positioned horizontally regardless of the membership categorization of the participating companies in both Consortiums I and II, was effective in determining the direction of research with a wide-ranging view. What situational analysis did the authors make in setting up the technical advisory committee? Also, can you explain in more detail what kind of function you expected from the committee?

Answer (Atsushi Masuda)

In Consortium I, there was no categorization of the participating organizations, but I think this was the reason for the differences in interest among the members. The greatest reason we set the member categorization in Consortium II was, as described in Chapter 4, to smooth out the consortium management by resolving the differences in interest among the members.

Since the Consortium was established by the demand of material manufacturers, the Consortium members were composed mainly of the material manufacturers. Many photovoltaic manufacturers kept the module reliability secret as know-how to themselves, and it was difficult to have them participate as organizations. On the other hand, the management was concerned that the findings of the photovoltaic manufacturers could not be utilized if the research was conducted only by the material manufacturers and collaboration between the two did not occur. Therefore, we asked for the participation of people who could provide wisdom to the Consortium as individuals rather than organizations. I added this aim in Chapter 2. The management, the invention review, and the technical advisory committees were not equal. The technical advisory committee was a permanent committee set under the management committee. The invention review committee was a temporary committee that convened only when there was a request from the inventors and was deemed necessary.

4 Results of the Consortium and future prospect

Question (Akira Kageyama)

In the first draft, you write, “This article explains only about the establishment and management of the Consortium, and please refer to the Reports for the results.” However, people would be curious to know what results were obtained under the support of your management. Therefore, can you list the titles of five or six major results and add a few lines of explanation?

I think the reliability evaluation and lifetime prediction technologies will contribute greatly to the future photovoltaic industry. Can you describe, as much as you can, the specific movements on how the results obtained will be carried on and developed further?

Answer (Atsushi Masuda)

As you indicated, I described the six representative research results of the Consortium in Chapter 6. The utilization of academic and fundamental findings obtained in this Consortium in application R&D such as the “Next-Generation Crystalline Silicon Photovoltaic Consortium,” whose objective is to develop high-quality crystalline silicon photovoltaic cells using thin wafers, is highly significant, and there is much potential. I added the cases where our results led to a new government project and where we obtained a result worthy of a press release in the succeeding individual joint research, to make Chapter 8 more complete. This Consortium was conducted with the intention to academically systematize the research backed by scientific evidence, and I think this led to the next development.

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
Revised February 16, 2012
Revised April 17, 2013
Revised May 9, 2014
Revised April 1, 2015
Revised October 1, 2015

1 Types of articles submitted and their explanations

The articles of *Synthesiology* include the following types:
• Research papers, commentaries, roundtable talks, and readers' forums
Of these, the submitted manuscripts of research papers and commentaries undergo review processes before publication. The roundtable talks are organized, prepared, and published by the Editorial Board. The readers' forums carry writings submitted by the readers, and the articles are published after the Editorial Board reviews and approves. All articles must be written so they can be readily understood by the readers from diverse research fields and technological backgrounds. The explanations of the article types are as follows.

① Research papers
A research paper rationally describes the concept and the design of R&D (this is called the scenario), whose objective is to utilize the research results in society, as well as the processes and the research results, based on the author's experiences and analyses of the R&D that was actually conducted. Although the paper requires the author's originality for its scenario and the selection and integration of elemental technologies, whether the research result has been (or is being) already implemented in society at that time is not a requirement for the submission. The submitted manuscript is reviewed by several reviewers, and the author completes the final draft based on the discussions with the reviewers. Views may be exchanged between the reviewers and authors through direct contact (including telephone conversations, e-mails, and others), if the Editorial Board considers such exchange necessary.

② Commentaries
Commentaries describe the thoughts, statements, or trends and analyses on how to utilize or spread the results of R&D to society. Although the originality of the statements is not required, the commentaries should not be the same or similar to any articles published in the past. The submitted manuscripts will be reviewed by the Editorial Board. The authors will be contacted if corrections or revisions are necessary, and the authors complete the final draft based on the Board members' comments.

③ Roundtable talks
Roundtable talks are articles of the discussions or interviews that are organized by the Editorial Board. The manuscripts are written from the transcripts of statements and discussions of the roundtable participants. Supplementary comments may be added after the roundtable talks, if necessary.

④ Readers' forums
The readers' forums include the readers' comments or thoughts on the articles published in *Synthesiology*, or articles containing information useful to the readers in line with the intent of the journal. The forum articles may be in free format, with 1,200 Japanese characters or less. The Editorial Board will decide whether the articles will be published.

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.
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, for subsections, 1.1.1.1, 1.1.1.2, 1.1.1.3.
3.3.2 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, image files (resolution 350 dpi or higher) should be submitted. In principle, the final print will be in black and white.
3.3.5 For photographs, image files (resolution 350 dpi or higher) should be submitted. In principle, the final print will be 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).

Website – [No.] Author(s) name (updating year): Title of a web page, Name of a website (The name of a website is possible to be omitted when it is the same as an author name), URL, Access date.

4 Submission

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

Synthesiology Editorial Board
c/o Public Relations Information Office, Planning Headquarters, National Institute of Advanced Industrial Science and Technology(AIST)
Tsukuba Central 1 , 1-1-1 Umezono, Tsukuba 305-8560
E-mail: synthesiology-ml@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

This is the ninth year since the launch of *Synthesiology*. In this issue, we deliver four papers, “Developing a leading practical application for 3D IC chip stacking technology,” “Securing a stable supply of critical raw metals,” “Scenario in synthetic-type research: its role and description,” and “Consortium style study on the development of highly reliable photovoltaic modules and acceleration test methods.” Although the contents of the research are diverse, the papers provide the summary and description of R&D processes and specific case studies for utilizing the developed technologies in society, such as the efforts on practical utilization, efforts on resource procurement, and efforts on establishing a consortium where the companies can develop common fundamental technologies. These are records of activities to fill in (to overcome) the “valley of death” that lie between the research activity and social contribution, which is the objective of *Synthesiology*.

In the Phase IV medium- to long-term plan, AIST is expected to strengthen its function as the “bridge” between research and commercialization. Therefore, these articles may provide great hints for how the research potential of individual researchers can be brought out to achieve (to succeed in) practical utilization and commercialization.

As described in the “Scenario in synthetic-type research: its role and description,” while most papers are incomprehensible to the readers of other fields, the papers published in *Synthesiology* are written in a form that can be understood by readers and reviewers who are from different fields. I hope you enjoy reading the articles.

(Masaharu TAKAHASHI, Executive Editor)

Aim of *Synthesiology*
— Utilizing the fruits of research for social prosperity —

There is a wide gap between scientific achievement and its utilization by society. The history of modern science is replete with results that have taken life-times to reach fruition. This disparity has been called the *valley of death*, or the *nightmare stage*. Bridging this difference requires scientists and engineers who understand the potential value to society of their achievements. Despite many previous attempts, a systematic dissemination of the links between scientific achievement and social wealth has not yet been realized.

The unique aim of the journal *Synthesiology* is its focus on the utilization of knowledge for the creation of social wealth, as distinct from the accumulated facts on which that wealth is engendered. Each published paper identifies and integrates component technologies that create value to society. The methods employed and the steps taken toward implementation are also presented.

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Highlights of the Papers in *Synthesiology*

Research papers

Developing a leading practical application for 3D IC chip stacking technology
—How to progress from fundamental technology to application technology—
M.Aoyagi, F.Imura, F.Kato, K.Kikuchi, N.Watanabe, M.Suzuki, H.Nakagawa, Y.Okada, T.Yokoshima, Y.Yamaji, S.Nemoto, T.T.Bui and S.Melamed

Securing a stable supply of critical raw metals
—Efforts and issues for the securement of rare-earth resources—
T.Takagi

Scenario in synthetic-type research: its role and description
—An investigation from Synthesiology papers—
A.Ono, M.Akamatsu, and N.Kobayashi

Article

Consortium style study on the development of highly reliable photovoltaic modules and acceleration test methods
—Management of the "Consortium Study on Fabrication and Characterization of Solar Cell Modules with Long Life and High Reliability"—
A.Masuda and N.Igawa

Editorial policy
Instructions for authors
Aim of *Synthesiology*

"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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