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Synthesiology

English edition

Development of thin-film multi-junction thermal converters

Green photonics for laser-based manufacturing

An IT system development framework utilizable without expert knowledge:MZ Platform

Synthesiology editorial board

2015

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Highlights of the Papers in *Synthesiology* Volume 8 Issue 3 (Japanese version Aug. 2015)

Synthesiology is a journal that describes the objectives and the social value of research activities that attempt to utilize the results in the 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**

Development of thin-film multi-junction thermal converters
— Establishing metrological traceability system for AC voltage standard —
An accurate AC voltage standard at the national standard level is calculated by comparative measurement of the DC voltage standard and AC voltage using a thermal converter. For the provision of standards for AC voltage, there have been demands from industry for the expansion of the range of voltage and frequency. Also, in the calibration laboratories, a slightly low precision calibration standard that used a method different from thermal converters was used due to the problem of operability and durability, and the standard supply system was not necessarily sufficient. Therefore, Fujiki (AIST) *et al*. set the goal of developing a thermal converter that could be applied both as the national standard as well as a calibration standard. They created the scenario from elemental technology development to product realization by considering the issues including the improvement of uncertainty required for national standards, the expansion of the standard range, and the operability, durability, and environmental resistance needed for calibration standards. They succeeded in developing a product that fulfilled the set goal.

Green photonics for laser-based manufacturing
— Photonics contributes to a sustainable society in the "photon century" —
The scenario and selection-synthesis of elemental technologies to realize green manufacturing processes and products through a systematic overview of material processing using laser was considered. New technologies developed according to this scenario by Niino (AIST), including the cutting of carbon fiber strengthening resin, surface reformation of the fluoride resin, and fine processing of transparent hard brittle material such as quartz glass are presented as examples. All the examples are difficult to process at high speed and with high quality by ordinary laser processing or other competitive processing technologies. For the practical use and diffusion of these technologies, the important points are the optimization of the prototype to total manufacturing process and the pursuit of high added value through the application of this technology.

An IT system development framework utilizable without expert knowledge: MZ Platform
— Toward end-user development in manufacturing industry —
Sawada (AIST) *et al*. developed the MZ Platform, a tool that enables construction and operation of IT systems by manufacturing engineers who may not have advanced expertise. It is a component system that could be used widely, but the components were constructed through the development of a practical system. To diffuse this system, seminars were held, a consortium was established, technology was transferred to software vendors through TLO, and support including technical instructions by public research institutes was organized. Success cases of the introduction of this tool include the following: a system to collect job performance in a plastic mold injection company; an ordering, manufacturing, and stock management system in the metal surface treatment industry; and an ordering, subcontracting, and progress management system in the mold manufacturing industry. The success factors of the cases are considered.

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Development of thin-film multi-junction thermal converters

— Establishing metrological traceability system for AC voltage standard —

Hiroyuki FUJIKI*, Yasutaka AMAGAI and Hitoshi SASAKI

[Translation from *Synthesiology*, Vol.8, No.3, p.127-144 (2015)]

Thermal voltage converters have been widely used in the electric standard field as a major method to derive AC voltage standards from DC voltage standards. However, there are only a limited number of organizations that are capable of fabricating thermal voltage converters. Furthermore, establishing AC-DC voltage standards has been constrained by the lack of high-quality thermal converters. High-quality thermal converters are used only by national metrology institutes (NMIs) because the conventional thermal converters are too fragile for many calibration laboratories. The National Institute of Advanced Industrial Science and Technology (AIST) has developed new thin-film multi-junction thermal converters (TFMJTCs) to realize a reliable high-performance thermal converter. Development of a durable TFMJTC with a heater on an aluminum nitride (AlN) substrate is expected to make significant contribution to Japanese calibration laboratories.

Keywords : AC-DC transfer difference standard, AC voltage standard, thermal converter, calibration, metrological traceability

1 Introduction

Today, the great majority of equipment used in production sites or the fields of information technology and scientific measurements employs electric signals for measurements, and it is not an exaggeration to say that voltage and current measurements have been used in most measurements. We believe that making reliable quantities of electrical standards consistently available will substantially contribute to the development of our society. The growing need these days for precisely measuring electric power, which is a derived quantity based on a voltage, current, and phase angle, has also increased the demand for improved accuracy of AC voltage standards.

A wide range of AC voltage standards is required by the industrial community. Specifically the voltages range from 1 μV used in medical equipment and micro electric power measurements, several millivolts to several hundreds of volts used in general-purpose electronic devices to several tens of kilovolts used in electric power facilities. The frequency range is also broad: 0.01 Hz used for vibration measurements, agitation of chemical agents and AC measurements of physical properties such as battery measurements, the commercial frequencies (50 Hz and 60 Hz), frequencies used for harmonics measurements (the order of 10 kHz, approximately the 100th order of the commercial frequencies), medium frequencies associated with the wireless power transmission technology (from several tens of kHz to several tens of MHz), and the order of GHz used for communications. The traceability of measurements is required for most of the range stated above. National metrology institutes and calibration laboratories have established relevant measurement standards, operate and maintain these standards, and provide calibration services.

The method that can derive an AC voltage standard with the highest precision is the AC-DC transfer method,[1] in which a thermal AC-DC converter (thermal converter) is used to compare an AC voltage with a DC voltage standard. Therefore, AC-DC transfer standards have been supplied as national AC voltage standards. With respect to the provision of AC-DC transfer standards, the AC-DC transfer differences of a thermal converter are calibrated, which correspond to the conversion error from a DC voltage to an AC voltage. In other words, AC standards are provided to calibration laboratories by calibrating their thermal converters. As explained below, however, the conventional thermal converters are designed in a way to achieve the highest possible precision, which causes inherent structural restrictions to make them hard to be handled owing to the vulnerability to overcurrents and impact. As a result, they have not come into widespread adoption among calibration laboratories or in the industrial community. The majority of calibration laboratories and the industrial community carry out calibrations of AC voltage standards by using standard AC voltmeters and AC generators, and therefore they fail to benefit from the biggest advantage of thermal converters, namely stability. Meanwhile the range of AC voltage standards provided by calibration laboratories to the industrial community in Japan has not been sufficient enough because it is difficult to expand the range of AC voltage standards when AC voltmeters or AC generators are used as reference.

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To establish a system to provide AC voltage standards domestically, it is also important that the Japanese standard is recognized internationally. In international comparison for the AC voltage standards, a thermal converter is used as the transfer device to check the equivalence of the AC voltage standards in conjunction with the result of an international comparison of DC voltage standards. In addition to international comparison, peer review of the technological capability for AC-DC transfer standards is carried out by a standard expert to register the calibration and measurement capabilities (CMCs), which indicates the capabilities of calibrating and measuring of the national metrology institutes in various countries. The CMC is necessary for mutual recognition among the national metrology institutes in various countries, where metrological traceability systems of various countries are mutually trusted and calibration results based on the national standards of other countries are accepted by each country as they are considered equivalent to those of its own country. When a product is exported, its test report issued by a testing laboratory in an exporting country can be accepted based on inspection of records by an importing country as long as the testing instruments are traceable to relevant CMC-registered national standards.

Although thermal converters are indispensable not only for national standards but also for providing AC voltage standards to the industrial community as discussed earlier, there are only a small number of metrology institutes that are capable of providing them because of the difficulty in their fabrication. In the 1960s when the research and development of AC voltage standards based on thermal converters was actively carried out, as well as in the 1990s when improvement of the accuracy of AC voltages was conducted, there were researchers and private companies developing thermal converters.[2][3] In the 2000s, however, it became difficult to obtain high-precision thermal converters because of the decline of private thermal converter manufacturers and retirements of researchers at national metrology institutes. In particular, there were no organizations that provided thermal converters capable of maintaining the highest accuracy since around 2005.

We have developed practicable thermal converters for the purpose of providing the highest-precision thermal converters that can be used for national standards. In the development, we fabricated easy-to-use, usability-oriented thermal converters by improving their performance and applying durable structure design, so that they would be widely adopted by calibration laboratories and measuring instrument manufacturers. The fabrication process was also revised and simplified to a great extent compared with the previous one so that it became easier to improve manufacturing yield and to hand down fabrication techniques, enabling stable provision of thermal converters as well as the establishment of a domestic system for AC voltage standards (Fig. 1).

2 Social objectives of AC voltage standards

In recent years, improvement of precision and reliability has been strongly demanded in measuring instruments such as voltmeters, wattmeters, electric indicators, and electronic sensors, widely used in research and development and production sites for the purpose of product quality control, performance evaluation, conformance tests, and environment monitoring. Meanwhile, the globalization and standardization of products are also advancing rapidly, which forces products made in Japan to comply not only with domestic standards but also with international standards before they are exported. At present, manufacturers are strongly required to address product liability of their products nationally and internationally and assure the measurement results delivered by inspections. Electrical products are required to undergo product inspection including voltage tolerance tests when being shipped, and it is important to ensure the reliability of the measuring instruments used for such inspection. For instance, UL standards issued by Underwriters Laboratories Inc. (UL), a safety assessment institution, requires measuring instruments used for inspecting electrical appliances used in the United States to be traceable to the national standards. If there is serious discrepancy in measuring results due to

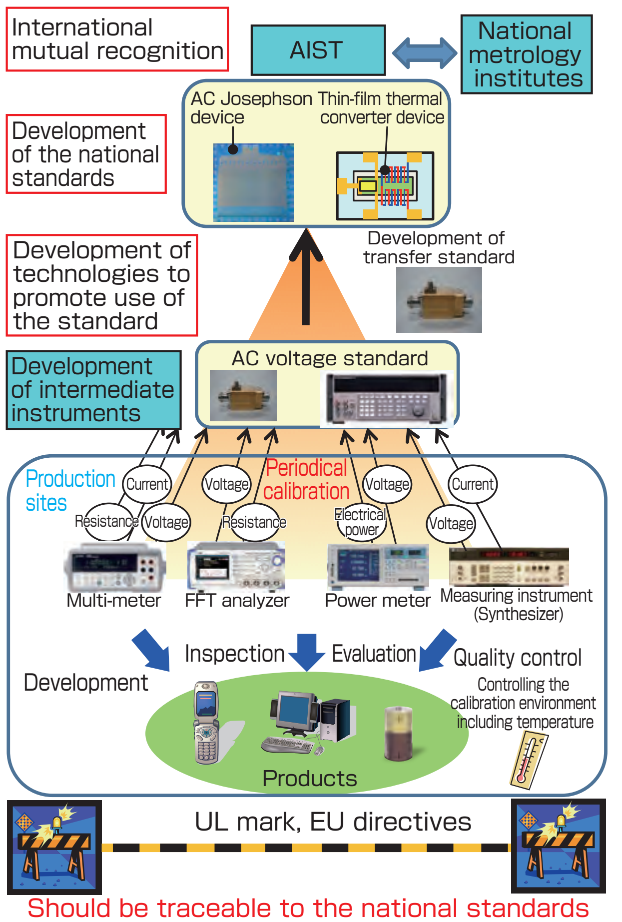

Fig. 1 Scenario to establish the domestic system for the AC voltage standard

the failure of measuring instruments, products may not be allowed to be exported to the United States. In Europe, the Communauté Européenne (CE) marking scheme has been implemented as well.

Measuring instruments required to be traceable to the national standards must be calibrated regularly (usually once a year) to guarantee results of inspections and measurements. Figure 2 shows the traceability system of electric power meters as an example where the calibration of the AC voltage standard is demanded. Submission of traceability system charts is frequently requested by customers when products are exported or examined or when some regulations are applied.

The upper-tier reference standards[Term1] managed by quality assurance departments in companies and inspection equipment used in industrial operations are not quite stable owing to physical disturbance such as ambient temperature, humidity, and vibration, and therefore their output values are influenced by such external factors. To address this problem, the quality assurance department in charge of products needs to have relevant measuring instruments calibrated periodically to maintain their reliability. In general, the quality assurance department uses the upper-tier reference standards of the company to periodically calibrate their working standards that are used for inspections in their manufacturing. The upper-tier reference standards of the quality assurance department are, in turn, calibrated by an external third-party calibration laboratory, which is traceable to a national metrology institute. In this way, as shown in Fig. 1, the traceability of inspection equipment used in production sites is established.

Most measuring instruments used in production sites are fixedly installed in production lines or other locations and kept stationary as much as possible. Measuring instruments, therefore, are usually calibrated in place under field environment. Quality assurance departments of companies manage their calibration facilities by giving consideration to stability of the calibration equipment, physical disturbance, and degradation of calibrated values over time. Ensuring reliability of the calibration equipment is important to avoid the delay of product delivery caused by imperfection in inspection before shipment since customers frequently request quick delivery Manufacturing companies receive many inquiries concerning conformance to specifications and pirated goods. Measurement traceability is essential to assure inspection results of the products in question. As explained above, quality assurance departments use calibration services provided by calibration laboratories to manage values given by their calibration instruments. Additionally, in the case of AC voltage standards, specific measurement techniques need to be adopted to appropriately address the effects of stray capacitance, impedance characteristics, load effects, and reflections. In the high frequency range, measurement results can easily change due to a slight difference in the measurement conditions. There is, therefore, the strong need for reliable upper-tier reference standards to ensure the validity of the company's measurement capability. In addition, there is an increasing demand for stable easy-to-use equipment. It is not unusual that tens to hundreds of measuring instruments need to be traceable to the national standards in a production site. For the entire manufacturing industry, therefore, the development of stable and easy-to-use measuring instruments is critical to reduce the workload and expenses associated with the calibration of measuring instruments and the management of production

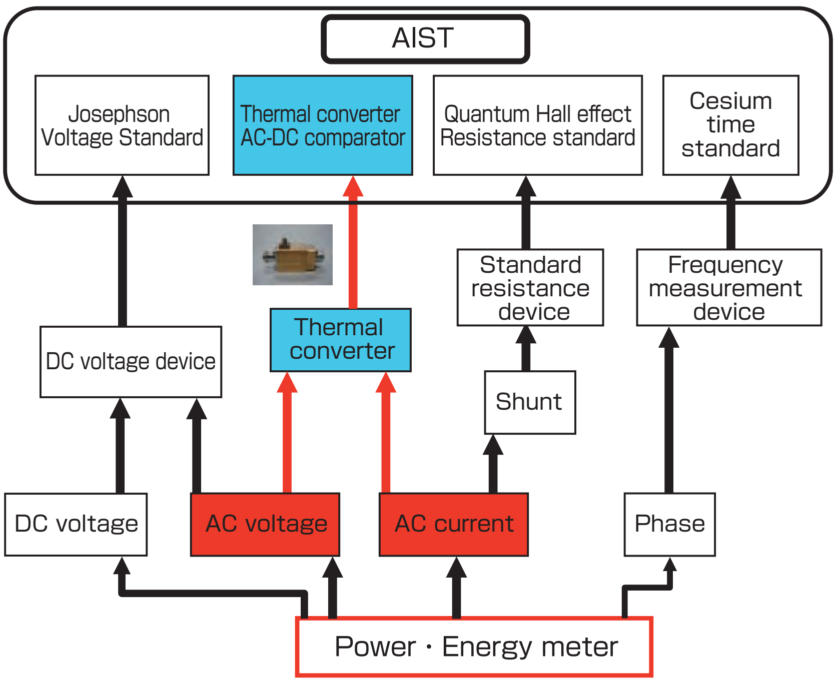

Fig. 2 Traceability system of power meters and energy meters

lines, which is expected to contribute to the improvement of competitiveness. As the reliability of measurements is essential for the improvement of product quality, standardization, security and safety, there is an urgent need to realize stable provision of the electric standards.

3 AC-DC transfer standards used to derive AC voltage standards

AC voltage and current standards are physical standards widely used as base quantity in the electrical industry including the electronics industry, the electric power energy industry and the electronic information communications equipment industry. On the other hand, AC-DC transfer standards are not familiar to the general public. There are only a few guides for AC-DC transfer standards written in Japanese. This chapter briefly explains the theory and techniques of AC-DC transfer standards and thermal converters, which constitute the basis of the remainder of this article.

3.1 AC-DC transfer standard

AC voltage standards are derived by comparing a DC voltage with an AC voltage via an AC-DC thermal converter. Heat plays a key role in this comparison. In accordance with the law of conservation of energy, it is defined that an AC voltage and a DC voltage are equal to each other when the amounts of heat generated by the heater in the converter are identical between the AC and DC voltages. The rms value of an AC voltage and that of a DC voltage can be compared on the basis of this definition, which in turn allows an AC voltage to be derived from a DC voltage. The system based on this comparison method is referred to as the “AC-DC transfer standard,” and the value corresponding to the conversion error from a DC voltage to derive an AC voltage is referred to as an “AC-DC transfer difference.” Up to the present, an AC voltage standard is established most accurately when it is derived from a DC voltage standard (Josephson voltage standard) via a thermal converter. This method is widely used by NMIs[1] (Fig. 3). In order to establish an AC voltage standard, therefore, the evaluation of AC-DC transfer differences of thermal converters as well as the development of a thermal converter is essential. For this reason, every national metrology institute has its own AC-DC transfer difference standard. The development of a thermal converter which features limited AC-DC transfer difference and is capable of evaluating AC-DC transfer difference is necessary for expanding the range of AC voltage standards in national standards and enhancing their performance. Although this is an important research subject, there are only a small number of metrology institutes that are capable of fabricating such a thermal converter. Consequently it is difficult to obtain high quality thermal converters consistently. Meanwhile the stable provision of thermal converters is indispensable to maintain and manage AC standards because thermal converters can be broken or deteriorated in the course of calibration operations. The stable provision is also necessary to make AC voltage standards with low uncertainty available to calibration laboratories.

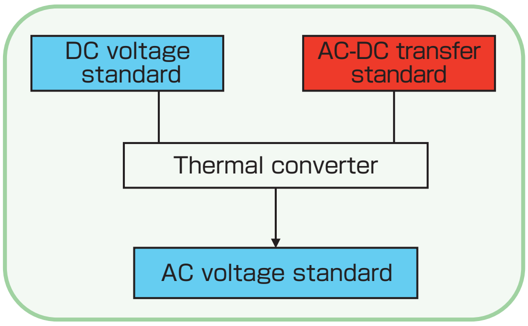

Fig. 3 Flow to derive the AC voltage standard

The causes of an AC-DC transfer difference are listed below since it is necessary to take into account the major factors of AC-DC transfer differences of thermal converters when the elemental technical challenges are discussed in Chapter 5. A thermal converter detects rises in temperature, with a thermocouple, induced by the Joule effect which is caused by the input voltage applied to a heater. Major AC-DC transfer differences of a thermal converter can be classified into the following three categories:

(I) Thermoelectric effect (dc offset): When a DC current flows through a thermal converter device, non-Joule heating/cooling occurs due to the Thomson and Peltier effects, which makes temperature distribution of the heater wire uneven. As a result, even when an AC sinusoidal wave voltage featuring the same rms value as a DC voltage is applied to the heater wire, the thermocouple outputs different voltages, which causes an AC-DC transfer difference (thermoelectric effect).[4]

(II) Low frequency characteristics: When the frequency of input AC voltage is not sufficiently higher than the thermal time constant of the thermal converter, the temperature of the heater wire changes along with the input voltage, causing periodical temperature variations (thermal ripples), which results in an AC-DC transfer difference.

(III) High frequency characteristics: In the frequency range of 10 kHz or higher, the frequency characteristic of AC-DC transfer difference is observed because the influences of the skin effect, stray capacitances in the input circuit and inductances cannot be eliminated from the device. At frequencies higher than 1 MHz, impedance matching needs to be taken into account.

Due to the causes listed above, the AC-DC transfer difference of an ordinary thermal converter features the frequency characteristics shown in Fig 4. In the frequency range from

100 Hz to 10 kHz, the high frequency characteristics and the low frequency characteristics are relatively small, and therefore the "thermoelectric effect" induced by non-Joule heat is dominant. While the AC-DC transfer differences described in (II) and (III) are evaluated by theoretical models, the AC-DC transfer difference described in (I) is evaluated by the FRDC-DC method, which is used to measure thermoelectric effect. [5]-[7]

3.2 Thermal converter

To date, four types of AC-DC converters have been developed: single-junction thermal converter (SJTC),[8] multi-junction thermal converter (MJTC),[9] thin-film multi-junction thermal converter (thin-film MJTC)[10][11] and solid-state thermal rms sensor.[12]

(1) Single-junction thermal converter (SJTC)

A single-junction thermal converter element (Fig. 5) is composed of a heater wire and a thermocouple. It is called "single-junction thermal converter" because a single thermocouple pair is used. The heat generated in the heater wire by an input DC voltage and that by an input AC voltage are measured with the thermocouple for comparison. To maintain the electrical insulation, the thermocouple is attached to the heater wire through an insulating bead. The heater wire and thermocouple are sealed in a vacuum glass bulb to improve the thermal insulation from outside. The length of the heater wire is designed to be short in order to

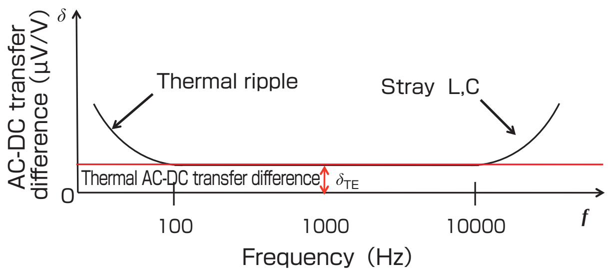

Fig. 4 Frequency characteristics of the AC-DC transfer difference of the thermal converter

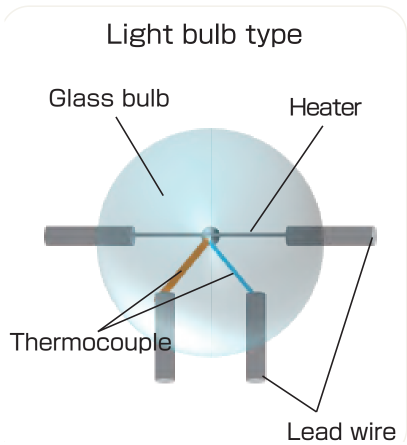

Fig. 5 Schematic diagram of a single-junction thermal converter (in a miniature bulb structure)

minimize the influences of stray inductance and capacitance and address the influence of reflections caused by impedance mismatch at high frequencies. The heater wire features a fine-line structure with a diameter of about 25 μm to suppress the influence of the skin effect and increase the resistance to a certain extent. The rated current is about 10 mA. The heater wire can be deteriorated or broken as it generates heat due to overcurrents. Since both the heater wire and the thermocouple feature a fine-line structure, single-junction thermal converters need to be fabricated manually under a microscope, which makes it difficult to mass-produce them and improve the yield.

Single-junction thermal converters came into use for measurements with accuracy of 1 ppm-level back in 1960s, and are still widely used in the field of AC voltage standards. Due to its simple structure, the SJTC elements feature small frequency characteristics up to high frequencies of about 1 MHz. The long-term drift of the AC-DC transfer difference is negligibly small. An AC-DC transfer difference, however, is generated by non-Joule heating or cooling which is induced by the Thomson and Peltier effects caused by the temperature distribution of the heater wire.

(2) Multi-junction thermal converter (MJTC)

Multi-junction thermal converters were developed to solve the problem of thermoelectric effect, which was particularly difficult to be evaluated. When the heater wire is straight in shape, temperature gradient is generated between high and low sides of the applied voltage. As shown in Fig. 6,[9] a multi-junction thermal converter adopts a stranded heater wire structure to reduce the unevenness of heat. In addition, a large number of thermocouples are used to uniform the temperature distribution of the heater wire, by which thermoelectric effect can be suppressed to 0.1 μV/V or less. Using a number of thermocouples makes it easy to measure AC-DC transfer differences because the output voltages increase to about 100 mV. However, the structure of a multi-junction thermal converter is the most complicated among thermal converters. To construct this structure, it is necessary to attach thermocouple wires with diameter of 20 μm to heater fine wires with diameter of 10 to 40 μm under a microscope,

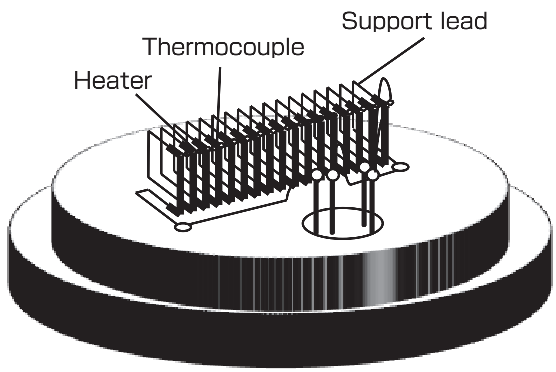

Fig. 6 Schematic diagram of a wired multi-junction thermal converter

which makes it difficult to mass-produce them. About 100 multi-junction thermal converters have been fabricated up to now, and one or two of them have been distributed to each of major national metrology institutes. Meanwhile multi-junction thermal converters cannot be used frequently since they are easily broken due to electric breakdown by static electricity. In calibration operations, therefore, single-junction thermal converters and thin-film multi-junction thermal converters to be explained next are usually used. In addition, the high frequency characteristics of multi-junction thermal converters are inferior to those of single-junction thermal converters owing to the complicated structure. Currently, wired multi-junction thermal converters are not in production.

(3) Thin-film multi-junction thermal converter (thin-film MJTC)

The development of thin-film multi-junction thermal converters (Fig. 7) started in the latter half of the 1980s when advanced micromachining technology was in wide use. A thin-film multi-junction thermal converter is a thin-film version of a wired multi-junction thermal converter which is very hard to be fabricated. The thin-film type generally has the structure of the multi-junction thermal converter to improve the small output, a weak point of SJTCs. This is why it is referred to as a thin-film MJTC in the world of standards. Thin-film thermal converters often adopt a loopback U-shaped heater structure to improve the unevenness of the temperature distribution. In the case of thin-film thermal converters the thickness of the substrate immediately below the heater needs to be adjusted to ensure thermal insulation around the heater. To make this adjustment possible, in the early 1990s, a technique was developed to deposit a thin film over a silicon substrate on which the area under the heater film was anisotropically etched. Thanks to this technique, thin-film multi-junction thermal converters were broadly adopted by national metrology institutes. However, the high frequency characteristic of a thin-film thermal converter is also inferior to that of an SJTC because of its complicated structure. At frequencies of 10 kHz or higher, the reproducibility of the frequency response of AC-DC transfer differences becomes deteriorated due to the effect of stray inductance and capacitance. Similar to SJTCs, it is not so easy to change the structure. The rated current of a thermal converter is about 10 mA. The wire will become broken when an overcurrent flows.

(4) Solid-state thermal rms sensor

Solid-state thermal rms sensors were developed by a U.S. measuring instrument manufacturer as practicable substitutes for single-junction thermal converters and multi-junction thermal converters. A solid-state thermal rms sensor does not employ a thermocouple but uses the temperature dependence of the base-emitter junction voltage V_{BE} of a transistor as the temperature sensing device to detect the temperature rise of the heater. The AC-DC transfer difference at around 10 Hz sometimes reaches the order of 100 μV/V because of the low thermal time constant. The thermal AC-DC transfer difference of a solid-state thermal rms sensor is a bit larger than that of a multi-junction thermal converter, and its uncertainty is a little higher. However, commercially-available solid-state thermal rms sensor type thermal converters are hard to be broken because of an embedded protection circuit against overcurrents. In addition, as a high-performance amplifier is used, the output voltage is high, which makes the measurements easier. The most common thermal converters among calibration laboratories are those using a solid-state thermal rms sensor. In order to use thermal converters as national standards, they must have a low uncertainty of the AC-DC transfer difference. It is also required that the frequency characteristic and other parameters of the AD-DC transfer difference can be evaluated. Therefore, solid-state thermal rms sensors have been commonly used as standards at calibration laboratories.

As shown in Fig. 8, voltage thermal converters are mounted in metal housings to determine electrical boundary conditions

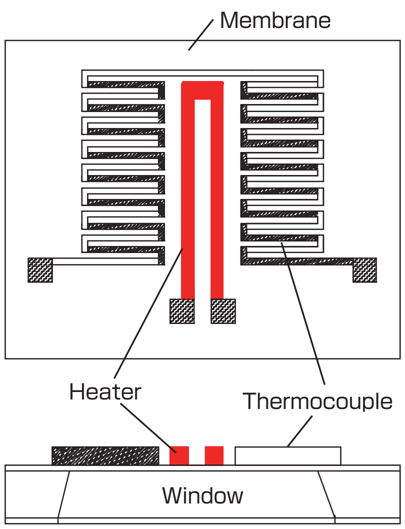

Fig. 7 Schematic diagram of a thin-film multi-junction thermal converter

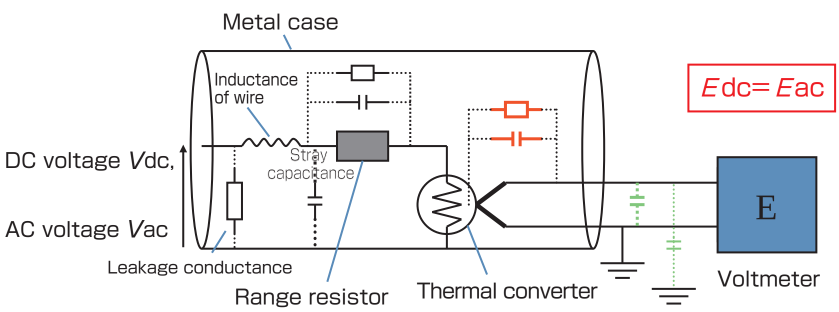

Fig. 8 Example of how a thermal converter is mounted

In order to expand the AC voltage range, the range resistor is placed in a metal housing and connected to the thermal converter in series. This made it possible to determine the frequency characteristics of the AC-DC transfer difference including the stray capacitance, stray inductance and parasitic resistance shown in the figure.

including the stray capacitance. The voltage is expanded by connecting resistors for dividing the voltage, namely range resistors, in series because the resistance of the heater in a thermal converter device is about 25 to 100 Ω due to structural restrictions. By using this method, the AC-DC transfer difference of the thermal converter, with the range resistors included, can be expanded up to 1,000 V.[13] AC voltage standards that can be established by an AC-DC transfer difference technique range between the orders of 1 mV and 1 kV in voltage and between the orders of 0.1 Hz and 100 MHz in frequency. Beyond these ranges, other methods have been adopted, i.e., a transformer or a thermistor is used or a sampling method is employed.[14][15] Recently, NIST has conducted the research and development to expand the frequency to the GHz order by using a thermal converter.[16]

4 Scenario for establishing AC voltage standards

The scenario required for establishing a domestic system of AC voltage standards consists of international mutual recognition, establishment of a high-precision national standard and provision of the standard to the industrial community (Fig. 1).

The project for expanding the range of the AC-DC transfer standards in Japan was launched in 2001 to address international mutual recognition and requests from the industrial community. The ranges of the AC-DC transfer standard provided in 2001 were 2 to 20 V in voltage and 40 Hz to 100 kHz in frequency, which were narrower than those of the AC-DC transfer standards provided by other countries' national metrology institutes. Moreover, the best measurement capacity was 10 ppm, which means that the uncertainty was also a bit high. In this situation, improvement of AC voltage standards was desired. While "development of a new standard device" is required for establishing a national standard, "development of utilization promotion technique" of the national standard is important for the proliferation of the calibration. Therefore, as shown in Fig. 1, the research and development of the national standard and the development of the utilization promotion technique of the standard must be carried out in parallel.

4.1 Establishment of the national standard

There are two approaches to derive AC voltage standards: 1) creation of ideal AC waveforms and 2) use of the AC-DC transfer method (Fig. 9). A universal standard that is reproducible, regardless of the time, place, and operator, and that features low uncertainty is desirable as the national standard. From this perspective, the quantum standard is ideal for the national standard of AC voltage standards. A representative example of the invention based on this method is shown in Fig. 9-1: to generate AC waveforms by using a Josephson DC voltage standard to vary the output values over time (AC voltage Josephson standard).[17] The existing DC voltage standards are realized by using the Josephson effect, which is a quantum phenomenon. Josephson DC voltages are determined by the number of junctions and the frequency of the microwave irradiated, which means that a very accurate voltage can be obtained if the frequency of the microwave is set accurately.[18] Currently, major national metrology institutes are conducting the research and development to create ideal AC voltages by using the Josephson effect. Also in the National Institute of Advanced Industrial Science and Technology (AIST), the DC voltage standard group has been taking the leading role in the development of AC voltage Josephson standards as candidate national standards of AC voltages.[19] Precisely speaking, AC voltages produced by this method have a stepwise waveform, but the voltage goes out of the quantized voltage in each step momentarily during the transition of the voltage, causing transient errors. To resolve this problem, the ways to avoid the transient errors are being studied. Even if AC voltage Josephson standards are realized, however, their voltage and frequency ranges are considered to be limited. In addition, there are some difficulties in using them in actual calibration operations in industrial operations. Currently, on top of the research and development to generate ideal AC waveforms, a system to calibrate AC voltage measuring devices and generators accurately is being developed by using an AC voltage Josephson standard and a thermal converter in combination.[20] The advantages of this method are twofold: 1) the uncertainty of the thermal

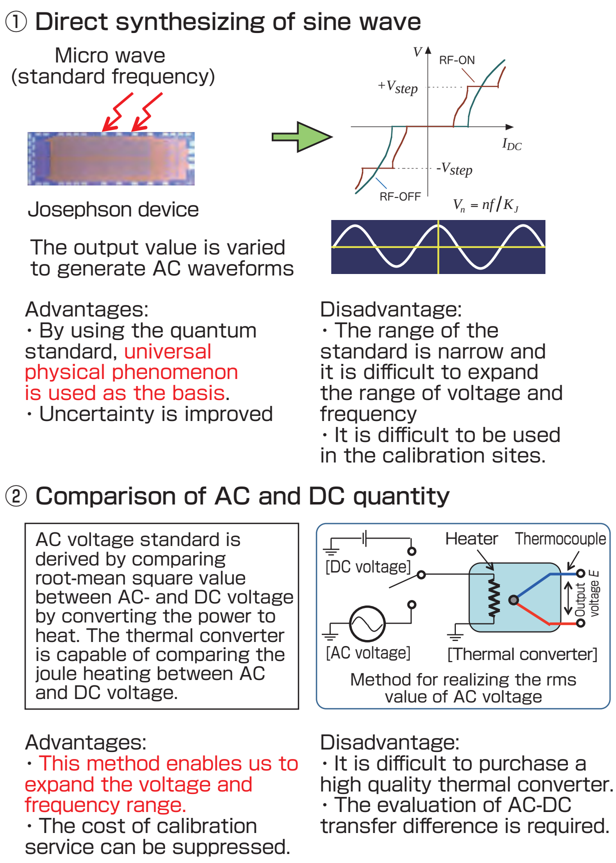

Fig. 9 Method for realizing the AC voltage standard

converter can be reduced and 2) the current system to provide AC voltage standards can be utilized.

The top-tier AC voltage standards currently available are realized by using the AC-DC transfer method shown in Fig. 9-2, which could remain as the national standard in the future because the transient errors of AC voltage Josephson standards are still unsolved. In order to use a thermal converter as a national standard, it is indispensable to evaluate the causes of the AC-DC transfer difference discussed in Chapter 3 and to improve its uncertainty, because the frequency characteristic of the AC-DC transfer difference varies depending on the resistor value and stray capacitance. (For a thermal converter used as a national standard, the value of the AC-DC transfer difference must be evaluated independently as the start point of the AC-DC transfer difference, rather than being calibrated by another standard.) Therefore, multiple thermal converters featuring different resistance and shapes are fabricated, so that the value of the AC-DC transfer difference can be determined by evaluating the variations in their AC-DC transfer differences. Similarly, in order to expand the range of AC voltages, thermal converters that can deal with the causes discussed in Chapter 3 must be fabricated. It is clear that multiple thermal converters with different characteristics need to be made available to establish the national standard. The reality was, however, that high-performance thermal converters were not easily available and therefore it was necessary to develop thermal converters for the scenario of the AC voltage system, as discussed above.

4.2 Utilization promotion technique for the national standard

Standard devices demanded by the industrial community are those that are affordable and usable in a wide range without placing a significant burden on the operation and maintenance. It is rare that the industrial community demands uncertainty equivalent to that of the national standard. Even in the case of the resistance standards with which quantum Hall effect is utilized[18] and the Josephson DC voltage standards, values provided by quantum standards are, for example, 10 kΩ and 10 V only, and a resistance bridge or a voltage divider is used to expand the range beyond. From the perspective of provision of standards, the quantum standards become less significant because it is not practical or realistic for quantum standards to cover the entire range of standard provision since there are other methods which easily realize these standards. As for AC voltage standards, as in the case with the resistance and DC voltage standards, even after quantum AC voltage standards are established in the future, low-cost and stable standard devices will be still necessary to expand the voltage range and calibrate measurement instruments used in the industrial community. Even when AC-DC transfer standards are replaced by AC voltage Josephson standards as the national standard, thermal converters will likely be continuously used for expanding the calibration services. In fact, in the field of the conventional DC voltage standards, the highest-precision calibration requests are made for Zener voltage standard devices. It can be anticipated that calibration requests for thermal converters will be continuously made in the field of AC voltage as well.

To expand the calibration services for AC voltage meters and generators to the industrial community, low-cost, robust, easy-to-use standard devices with a small degree of drift are essential. In implementing the scenario for the proliferation of standards, even when a sophisticated national standard is established, the industrial community cannot utilize calibration services unless appropriate standards traceable to the national standard are made available. If AC voltage meters or generators used in inspection sites for general industrial products were employed as the standards, they might not be able to fully benefit from the sophisticated national standard because of the possible degradation of the calibration values caused by long-term drift and disturbance such as temperature and humidity. High-performance thermal converters are stable with less than 1 ppm of long-term annual drift in the AC-DC transfer difference at about 1 kHz, and feature very little voltage dependency. If calibration laboratories and calibration departments in companies can use a thermal converter as a standard, they can obtain a high-precision, stable standard. If AC voltage values of an AC voltmeter instead of thermal converters are used for calibration, it will become difficult to further expand the range of calibration with low uncertainty, which may pose the risk to narrow the range of calibration services provided to the industrial community. Meanwhile the conventional thermal converters were fragile and could be damaged even when they were handled with care. It was necessary, therefore, to improve the durability of thermal converters in order to expand the range of calibration services provided to the industrial community. In addition, the rated voltage of the conventional thermal converter was 1 V, and therefore a range resistor needed to be used to expand the range. So there was a need to expand the voltage range of a thermal converter. The development of a new thermal converter is also in line with the objectives of the stable provision of AC voltage standards to the industrial community and further proliferation. As discussed above, as a challenge of the calibration techniques for the industrial community, it was considered necessary to develop a thermal converter that can be used as a standard.

5 Development of a thin-film thermal converter

To realize the national standard and extend the calibration services of AC voltage standards, we have developed a technique to fabricate thermal converters easily and designed a new thermal converter that can solve performance issues. The development of a thermal converter practicable enough to be used in the industrial community makes it possible to establish and maintain the national standard, and provide a high-precision standard to the industrial community.

5.1 Elemental technical issues

We have developed a new thermal converter as we believed that the fabrication of a thermal converter would contribute a lot to the establishment of the AC voltage standard system when we looked at the scenario for deriving the AC voltage standard discussed in Chapter 4. In this section, the technical issues in relation to the fabrication of thermal converters are presented.

(1) Issues in the fabrication method

In the case of a single-junction thermal converter having a miniature bulb structure (Fig. 5), although it is desirable to use platinum, which can suppress the Peltier effect and features a similar coefficient of thermal expansion to glass bulbs, for the pole to support the heater wires, highly-skilled craftspersons need to be used to weld platinum to Evanohm®, the material of the heater wires. Moreover, there are only a few craftspersons in the world who are capable of fabricating high-quality single-junction thermal converters because it is difficult to mount thermocouple leads with diameter of 20 μm at the very center of the heater fine wire with diameter of about 25 μm and seal them in vacuum. We have not been able to purchase thermal converters in which a platinum wire is used since 2005.

A thin-film thermal converter shown in Fig. 7 also had some issues in its fabrication. PTB, a German national metrology institute, fabricated thin-film thermal converters by forming a heater thin film on a silicon substrate and used them for the standard provision. The operating principle of a thermal converter is based on the measurement of temperature rise in the heater wire. In order to ensure the thermal insulation around the heater film, the silicon substrate immediately below the heater film is chemically etched, which makes that part of the substrate becomes thinner. This structure applies excessive stress to the heater film, and therefore a buffer layer needs to be deposited to relax the stress. Without a buffer layer, cracks were sometimes developed on the heater film and thermocouple film. As discussed above, the fabrication of a thermal converter requires specific know-how including the conditions of etching and buffer layer growth. On top of that, the method to fabricate resistive thin films with a low temperature coefficient and the technique to fabricate the thermocouple thin film composed of specific materials needed to be established because the temperature coefficient of the heater film and the output characteristics of the thermocouple film have influences on the AC-DC transfer difference. The PTB-type thin-film thermal converter shown in Fig. 7 has been also hardly available because the staff member in charge left PTB.

(2) Technical issues with thermal converters

It is also important to discuss the design of thermal converters. The conventional thermal converters had a couple of challenges: difficulty in the fabrication due to their structure and limitation in their performance. The conventional thermal converters are designed in a way to achieve the highest precision of AC voltage standards. Single-junction thermal converters have a short heater wire to achieve a frequency characteristic suitable for the evaluation of uncertainty at high frequencies of 10 kHz or higher. Since the wavelength of AC voltage at 1 MHz is about 300 meters, a heater wire of a few centimeters in length is equivalent to a few ppm order when the ratio of the wavelengths of the input frequencies is applied. When a ppm-order uncertainty is required for AC voltages, a shorter heater wire is more suitable because a lumped constant model can be used for calculation. In order to increase the input resistance of the circuit so as to observe the heat generated by the heater, however, the heater wire must be fine enough to achieve resistance of about 25 to 90 ohms. Use of the fine heater wire also makes the evaluation of the uncertainty derived from the skin effect easier. On the other hand, the current level is limited to about 10 mA because the heater wire is surrounded by the vacuum, and the heater wire may be burnt off if an overcurrent exceeding the rated current by a few percent is applied. As it is difficult to change the structure of a single-junction thermal converter, its resistance and thermal time constant are hard to be changed. As a result, range resistors are needed to achieve a required input voltage. Also uncertainty gets higher at 100 Hz or lower due to the low-frequency characteristic discussed in Subchapter 3.1 (II).

The major objective of fabricating conventional thin-film multi-junction thermal converters (Fig. 7) was to evaluate the thermal AC-DC transfer difference described in Subchapter 3.1 (I). To achieve this objective, a hundred thin-film thermocouples are fabricated along the heater wire. When the frequency increases, electrical insulation gets weaker owing to the unavoidable capacitance between the heater and the thermocouples, resulting in a leakage of the input current into the measurement circuit on the thermocouple side.[21] As the amount of the leakage current is determined by the circuit to measure output from the thermocouples, reproducibility gets poorer, by which the uncertainty gets higher. Since many thermocouples are used, the resistance of the thermocouples amounts to about 10 kΩ, which causes noises when the output voltage of the thermocouples is measured. In the case of thin-film multi-junction thermal converters, the rated current is also limited to about 10 mA and the thermal time constant is not easy to be changed.

One of the subjects for provision of calibration services in the industrial operations is the differences in the calibration environment. If AC-DC transfer difference of a thermal converter used in an industrial operation is considerably dependent on temperature and/or humidity, the reliability of calibration results may be deteriorated even when it is

Table 1. Technological elements for development of thermal converters

Elemental technology	Summary of development	Reasons/ grounds for setting	Relevant figures/ tables
(1) Issue in fabrication method: Simplification of fabrication	The conventional thermal converter in a miniature bulb structure is fabricated manually under a microscope by craftspersons, and therefore high level of skills are required. The fabrication method needs to be simplified.	Thermal converters are hard to obtain due to difficulty in their fabrication. Only limited organizations, even among national standard organizations, can fabricate thermal converters.	Fig. 5, Fig. 12, Table 2
(2) Issue in fabrication method: Adoption of thin films in a thermal converter	The etching technique is required for the conventional thin-film thermal converters. In addition, some sources of uncertainty of the AC-DC transfer difference are derived from structural restrictions.	A small thermal converter is required so that it can be used in general measuring instruments. In order to facilitate the use of thermal converters in industry, thermal converters with better usability need to be provided.	Fig. 7, Fig. 11, Fig. 12, Fig. 13, Table 2
(1) Technical issue: Improvement of the high frequency characteristics of the AC-DC transfer difference	In the conventional thermal converter, input current of a heater wire leaks into the measurement circuit on the thermocouple side due to stray capacitance between a heater and a thermocouple, causing poor reproducibility in the high-frequency region and becoming a major source of uncertainty.	Excellent reproducibility is required for a thermal converter to be used as the national standard. Calibration in the high frequency region is difficult even for the calibration laboratories. The high frequency characteristics need to be improved.	Fig. 7, Fig. 14
(2) Technical issue: Improvement of the heater resistor in a thermal converter	The heater resistance value of the common thermal converter is restricted, and the input voltage is limited. Through change in the structure of the thermal converter, a desired resistance value can be selected. In addition, precision may be degraded in the low frequency region by the fluctuation of temperature and variation of resistance value of the heater wires. The heater resistor needs to be improved.	For calibration laboratories, thermal converters that can be used in a wide voltage range are useful. In addition, it is desirable that uncertainty associated with calibration be small.	Table 2
(3) Technical issue: Improvement of the thermal AC-DC transfer difference	The AC-DC transfer difference at around 1 kHz represents one of the important performance indicators of a thermal converter. If the AC-DC transfer difference at 1 kHz is 1 ppm or below, the thermal converter can be used as the high performance national standard instrument.	For thermal converters that can be used as the national standards, the AC-DC transfer difference at 1 kHz should be 1 ppm or below.	Fig. 16, Fig. 17
(4) Technical issue: Improvement of durability	The rated current of a thermal converter is as small as 10 mA, and even a slight overcurrent can cause disconnection and destruction of heater wires. For wider use of thermal converters in the industry operations, durability of thermal converters needs to be improved.	Calibration laboratories and businesses often perform considerable number of calibrations. Thermal converters, therefore, must be hard to be broken.	Fig. 19, Table 2
(5) Technical issue: Improvement of low frequency characteristics of a thermal converter	When the thermal time constant of the thermal converter is in the order of 0.1 second, the AC-DC transfer difference increases at low frequency of 100 Hz or below, which will increase uncertainty of calibration. It is necessary, therefore, to improve the low frequency characteristics.	To improve uncertainty of AC voltage at the commercial frequency, it is necessary to improve the AC-DC transfer difference at low frequency of 100 Hz or below.	Fig. 17, Table 2
(6) Technical issue: Improvement of resistance of a thermocouple	The SN ratio is proportional to the output voltage, and inversely proportional to the square root of the output resistance R. When multiple thermocouples are mounted, the resistance value gets to 10 kΩ and the detection sensitivity is degraded. In order to improve the SNR, the resistance of thermocouples needs to be reduced as much as possible.	When the AC-DC transfer difference is evaluated at the ppm level as the national standards, the detection sensitivity needs to be high.	Fig. 10, Table 2
(7) Technical issue: Frequency characteristics of the AC-DC transfer difference of thermal converters	In order to improve ease-of-use of thermal converters to facilitate their wider use in the industry, frequency characteristics need to be made flat. The frequency characteristics (10 Hz to 1 MHz) of the AC-DC transfer difference need to be improved.	In the case of calibrations carried out in the industrial operations, it is desirable that the thermal converter features less-varied frequency characteristics in order to detect shift of calibration values caused by changes in the calibration conditions.	Fig. 17, Table 2
(8) Technical issue: Evaluation of environmental resistance of a thermal converter	Unlike in a calibration room, the environmental conditions including temperature and humidity may not be sufficiently controlled in the industrial operations. The environmental resistance of thermal converters needs to be evaluated and used as indices for use of thermal converters.	To promote usage of the standards in the industrial operations, it is important to evaluate the stability of thermal converters against environmental conditions.	Fig. 20, Fig. 21

calibrated periodically. In addition, if the AC-DC transfer difference features significant frequency characteristic, sometimes it can be difficult to notice deviations in calibration values attributed to the measurement conditions including the effect of cable length and the temperature changes. It is desirable, therefore, that thermal converters feature small frequency characteristic of the AC-DC transfer difference.

The technological elements for the development of thermal converters discussed above are summarized in Table 1. The conventional single-junction thermal converters and multi-junction thermal converters, which are hard to handle, are primarily used in national metrology institutes where the highest-precision is required. In the industrial community, while the proliferation of those thermal converters is very limited, solid-state thermal rms sensors are commonly used among the four types explained in Subchapter 3.2. However, solid-state thermal rms sensor type thermal converters need to be calibrated by other national metrology institutes because their structure does not allow direct determination of the causes of the AC-DC transfer difference discussed in (I) to (III) of Subchapter 3.1. The industrial community uses solid-state thermal rms sensor type thermal converters, which are calibrated by calibration laboratories using a single-junction thermal converter or a multi-junction thermal converter.

5.2 Design and development of a thermal converter

Change of the fabrication process, including simplification of fabrication, is required in order to solve the technical issues for the thermal converters described in Subchapter 5.1. The conventional thermal converter consists of a heater wire and a thermocouple, both of which are integrated into one body, and a failure of either component, if any, would result in malfunction of the thermal converter. There is also a problem in the actual fabrication. Since a heater wire and a thermocouple are fabricated on a same substrate, even if fabrication of either component succeeds in the preceding process, it can be degraded or damaged due to impacts of the subsequent process, which may result in yield drop. To address these problems, a new thermal converter is designed in a way to fabricate a heater and a thermocouple on two separate substrates. This design allows to realize the optimal fabrication conditions of a heater wire and a thermocouple independently, by which they do not affect each other. As a result, it is expected that the fabrication is simplified and the performance is improved. In addition, the new design imposes less restriction on the position of each component, compared to the integrated type, and makes it easier to change their forms and layouts. It is possible to improve the frequency characteristic that is dependent on the structure. By separating a heater and a thermocouple, which are key components of the thermal converter, the substrate etching process is eliminated and the stress-induced problems, such as the heater film delamination from the substrate and change of its characteristics are resolved. The fabrication process is significantly simplified, which is expected to lead to the yield improvement.

As for the materials of a heater and a thermocouple, Ni-Cr alloy and Bi-Sb are selected because they are the proven techniques for our research group. With respect to the heater resistor, we started with improvement of its temperature coefficient since one of primary causes of the AD-DC transfer difference is fluctuation of resistance along with temperature change which occurs when the temperature coefficient is too high. The resistance temperature coefficient of the Ni-Cr thin film before annealing is approximately 100 ppm/K, but when the Ni-Cr thin film is annealed, it can be reduced to as low as ±25 ppm/K. Annealing in nitrogen ambience is found effective to further reduce the temperature coefficient of the resistor to 10 ppm/K or below. It is assumed that in nitrogen atmosphere, it is heated by thermal conduction through contact with gas, resulting in higher uniformity in heat treatment, enabling strict control over the target annealing temperature. In our fabrication method of heater films, multiple substrates can be used simultaneously in a single vapor deposition process, which makes it possible to fabricate heaters in larger volume than the conventional thermal converter fabrication process.

Fabrication of thermocouple films is basically the same as the fabrication of the conventional thin-film thermal converter. The resistance of the conventional-type thermocouple, however, is as high as several kilo-ohms since approximately 100 pairs of thermocouples are connected in series. In order to improve the resistance, the structure of the thermocouple is changed as shown in Fig. 10. By inserting the Cu film between the Bi film and the Sb film, the contact resistance becomes considerably lower. We have succeeded in reducing the resistance from 4 kΩ to 400 Ω by reducing the contact resistance. We also attempted to increase the output voltage by fabricating thermocouple films on both sides of a substrate. To realize this structure, the following eight evaporation processes need to be performed to deposit thermocouple films on polyimide film by using the mask deposition technique: (1) the Bi film deposition, (2) the Sb film deposition, (3) fabrication of the thin Cu film for an electrode and (4) deposition of the Cu film between Bi and Sb films, and then the same four steps are performed on the other side of the substrate. The vapor

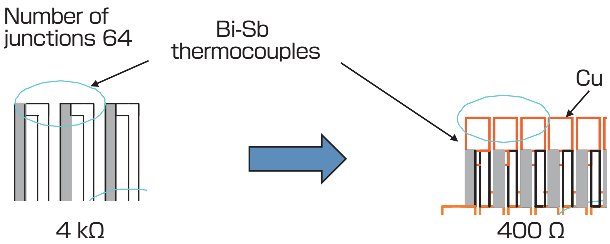

Fig. 10 Improvement of the thermocouple structure

deposition holder shown in Fig. 11 has been developed to fabricate multiple thermocouples at a time even in the complex thermocouple film fabrication process. This holder is effective in positioning the thermocouple film accurately and improving the yield, by which the fabrication method to realize high-volume production is established.

Figure 12 shows the structure of the thin-film thermal converter which we developed this time. The heater resistor and the thermocouple are fabricated separately as described above. The heater resistor and the thermocouple film that satisfy relevant specifications are selected to build a thermal converter. The 12 µm-thick polyimide film on which the thermocouple film is formed is supported by the alumina frame. The aluminum nitride chip on which the heater film is formed is mounted on the polyimide film by using the flip-chip bonding method. Since annealing of heater resistors can be performed independently as described above, the heater resistor is annealed before it is mounted on the polyimide film, which protects other components including electrodes and thermocouples from thermal effects. Thanks to this process recipe, it is now possible to apply the optimal annealing condition and the fabrication is simplified. The thermal converter fabrication is completed when the alumina frame on which the heater resistor and the thermocouple are mounted is covered with alumina. The size of the device is 2 × 1.5 cm, and it can be embedded into a measuring instrument.

Next, the improvement in performance is discussed. Since the structure and characteristics of the thermal converter are closely related, the structure is designed in a way to solve the technical issues presented in Subchapter 5.1. For the heater substrate, an aluminum nitride substrate with high thermal conductivity is adopted to prevent degradation and destruction of heater wires due to overcurrent. The AlN substrate also acts as a cooling heat-sink to release heat from the heater resistor, which improves durability significantly, compared to the thermally-insulated vacuum-sealed heater structure. It also becomes possible to expand the current range. In the case of this structure, the DC voltage and the AC voltage are compared not by directly measuring the temperature of the heater wire but by measuring the temperature rise on the aluminum nitride substrate. This structure allows for the thermal converter featuring the rated current of 200 mA.[22]

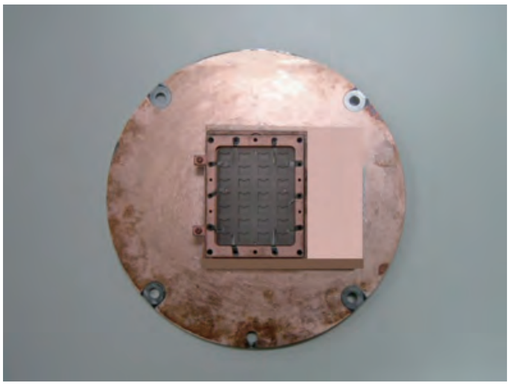

Fig. 11 A rectangle vapor deposition holder for fabrication of thermocouple films

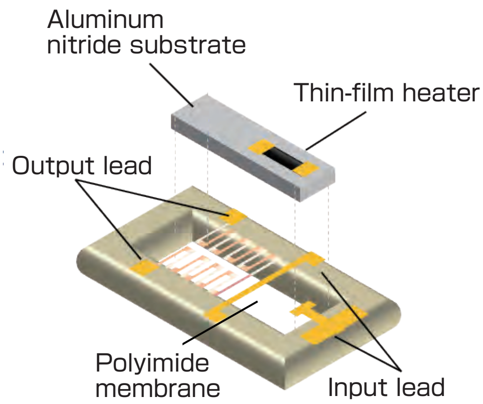

Fig. 12 Schematic diagram of a thin-film thermal converter

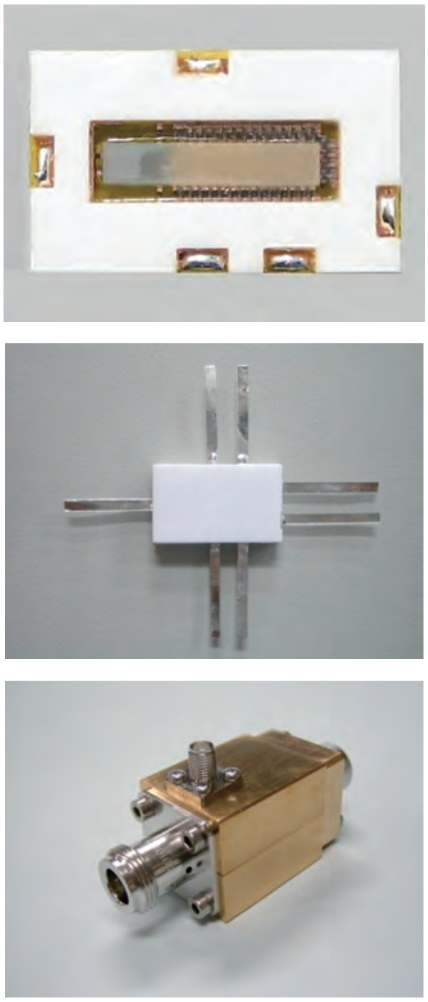

Fig. 13 Inside of a thin-film thermal converter device (top), appearance of a thin-film thermal converter device (middle) and a metal housing for a thermal converter (bottom)

The heater resistance can be changed more easily by adjusting the heater shape and the sheet resistance, compared with the conventional thermal converter. The heater length can be changed in the range of 0.1 mm to several millimeters. A desired resistance can be achieved by monitoring resistance during the formation of the heater film. The heater resistance value can be selected in the range of 1 Ω to 2 kΩ. For a thermal converter with 2 kΩ resistance, voltage of up to 20 V can be applied without using a range resistor which divides voltage for expansion of voltage. Any desired heater shape can be selected, such as the straight type which allows for calculation of the frequency characteristics and the U-shape type which can reduce thermal AC-DC transfer difference. In addition to selection of different resistance values, it is also possible to estimate AC-DC transfer difference by fabricating multiple thermal converters with different frequency characteristics.

The position of the thermocouple is changed from the conventional structure shown in Fig. 5, where it is located near the heater wire, to the position away from the input high side of the heater wire in order to reduce effects of stray capacitance between the heater wire and the thermocouple. By placing the thermocouple on the low side of the heater wire, the potential difference becomes smaller and the leakage current is reduced. The heater film occupies only a limited part of the aluminum nitride substrate as shown in Fig. 14, and the thermocouple detects temperature rise of the rest of the substrate. In the conventional thin-film thermal converter, since the area around the heater wire is thermally insulated, the heater and the thermocouple cannot be located away from each other.

Next a thermal time constant of the thermal converter is designed to improve the AC-DC transfer difference in the low frequency region. A thermal time constant is a value that represents the response characteristics of the output voltage of a thin-film thermal converter and it is also a parameter that determines the frequency characteristics of the thermal ripple in the low frequency region. In the case of the AC-DC transfer difference of the thermal converter, when the input voltage frequency f becomes lower, Joule heat generated in the heater wire oscillates between 0 to the maximum power at a double frequency $2f$. When the input frequency f is not high enough compared to a reciprocal ($1/\tau$) of a thermal time constant of the heater wire, the oscillation of a double frequency $2f$ also occurs for temperature of the heater. A time constant of a single junction thermal converter is around 0.1 s to 1 s, and an effect of the thermal ripple cannot be ignored in the low frequency region of 100 Hz or below. A thermal time constant of the thin-film thermal converter that we developed can be adjusted from 0.3 seconds to 4 seconds by changing the size of the aluminum nitride substrate. For example, the size of the substrate is 0.3 mm × 1.5 mm × 8 mm when the time constant is 2 seconds. The thermal time constant of the conventional thermal converter is closely related to its structure and it is difficult to change the thermal time constant independently. The new thermal converter is designed to change the thermal time constant without changing its structure significantly. Along with the improvement in the temperature coefficient of resistance of the heater wire, it becomes possible to improve the frequency characteristics of the AC-DC transfer difference of the thermal converter.

6 Characterization of the thin-film thermal converter

With respect to the performance of the developed thermal converter, the goal of this study is to improve durability and increase usability while keeping its performance high enough to be employed in the national standard instruments. This performance improvement is expected to facilitate a wide use of the new thermal converter in industry. In this chapter, we will describe the characterization of the newly-developed thin-film thermal converter.[23]

Firstly, a thermal converter of the same structure as the conventional thin-film type was built as a prototype to evaluate its characteristics (Fig. 15). As shown in Fig. 15, the heater film and the thermocouple film were fabricated on a polyimide film instead of a silicon substrate. The thermocouple is located along the heater wire. The frequency characteristics of the

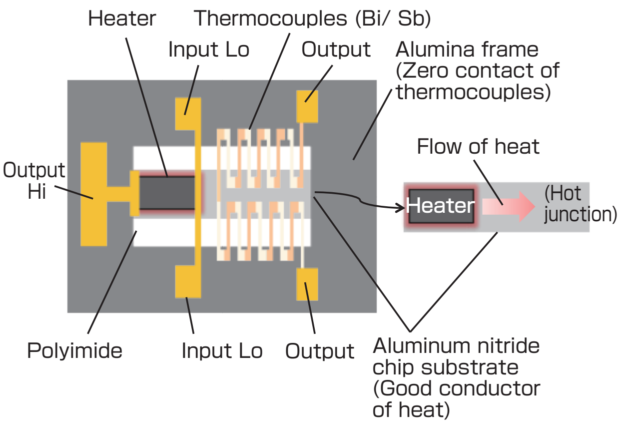

Fig. 14 Layout of a thin-film thermal converter

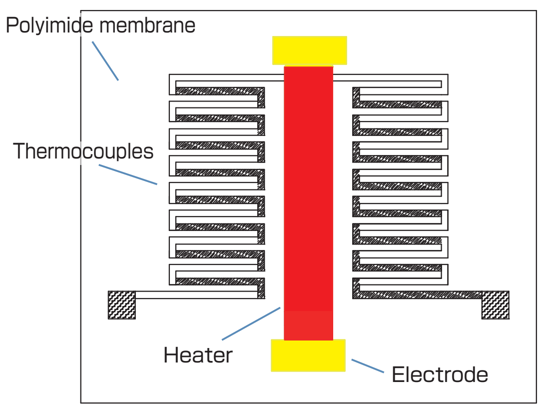

Fig. 15 Schematic diagram of a prototype of a thin-film thermal converter

AC-DC transfer difference of the prototype are shown in Fig. 16. The AC-DC transfer difference at around 1 kHz is approximately 5 ppm and it fails to satisfy Technical Issue (3) listed in Table 1. To be used as the national standard instruments, the thermal converter aims at achieving the AC-DC transfer difference of 1 ppm or below at the frequency of around 1 kHz. The failure to meet this aim is considered to be attributed to non-uniformity of the heat distribution of the polyimide film heater wire induced by the variance of heat inflow/outflow on the heater wire. At the frequency of 1 MHz, the AC-DC transfer difference of 10 ppm or more is observed. This is because the structure of the prototype does not take into account the frequency characteristics of the AC-DC transfer.

Next, the characteristics of the new thermal converter (Fig. 10) are reported. Figure 17 shows the measurement results of the AC-DC transfer difference of the thermal converter at the frequency of 10 Hz to 1 MHz. The dotted line in the figure represents the results of the conventional thermal converter, and the solid line represents those of the newly-developed thermal converter. Through the improvement in non-uniformity of the heater, the AC-DC transfer difference at around 1 kHz has been improved to 1 ppm or below. In order to evaluate the frequency characteristics of the AC-DC transfer difference, the model calculation of the frequency characteristics of the AC-DC transfer difference is performed with the resistance and stray capacitance taken into account. By fabricating the thermal converter shape in a way to strictly meet the design specifications, the AC-DC transfer difference of 10 ppm or below is achieved even at 1 MHz, which is totally different from the result shown in Fig. 16. With our new thermal converter, it is possible to freely change thermal time constant, resistance, shape or layout of the heater, all of which are the causes of the low frequency characteristics of the AC-DC transfer difference listed in Technical Issue (5) in Table 1. The size of the aluminum nitride substrate is adjusted to make the thermal time constant appropriate and the temperature coefficient of resistance is improved to 5 ppm/K or below. By taking these measures, it becomes possible now to fabricate the thermal converter whose AC-DC transfer difference is reduced to 10 ppm or below in a wide frequency range of 10 Hz to 1 MHz as shown with the solid line in Fig. 17. The values of AC-DC transfer differences for the conventional thermal converter were more than 10 ppm at low-frequency and high frequency ranges as shown with the dotted line in Fig. 17. Uncertainty of the AC-DC transfer difference of around 0.1 % is often acceptable in the industrial operations. By using our newly-developed thermal converter, the value of the AC-DC transfer difference can be deemed as 0, which means that Technical Issue (7) in Table 1 is solved.

Figure 18[23] shows the evaluation of Technical Issue (1) “High frequency characteristics of the AC-DC transfer difference” in Table 1. Figure 18 (a) shows the frequency characteristic of the prototype illustrated in Fig. 15, i.e. the conventional thermal converter in which the thermocouple is located along the heater wire. The open squares represent the measurement results obtained when a low-pass filter is inserted in the thermocouple output circuit while the solid circles represent the results obtained without using a low-pass filter. The difference of the two sets of measurement results suggests insufficient electrical insulation between the heater and the thermocouple. The AC-DC transfer difference constitutes a major source of uncertainty as it depends on the measurement circuit of the thermocouple. It needs to be evaluated, therefore, when a calibration laboratory uses the conventional thermal converter. Figure 18 (b) shows the results of the developed thermal converter. The same frequency characteristic is observed for both cases: with and without the low-pass filter. At the high frequency of 1 MHz, the difference between the two cases is within the range of variance of measured values. The results are good and comparable with those obtained with the thermal converter in which the thermocouple is moved near a zero potential electrode. The usability for calibration laboratories is improved.

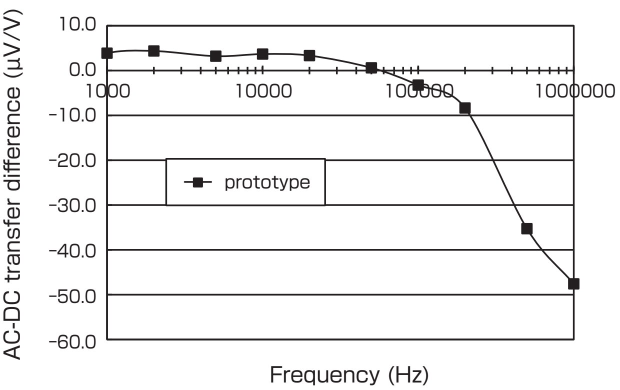

Fig. 16 Frequency characteristics of the AC-DC transfer difference of the prototype thin-film thermal converter

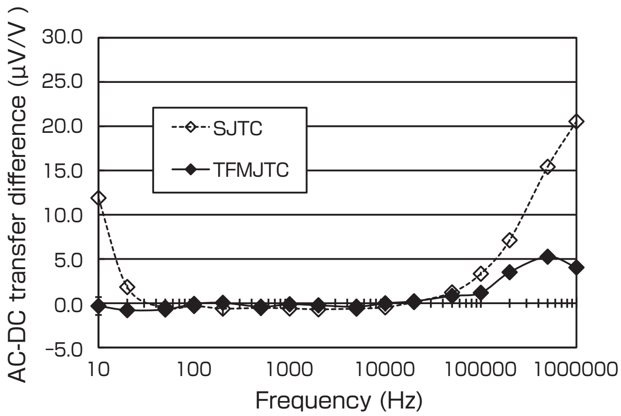

Fig. 17 Frequency characteristics of the AC-DC transfer difference of a single-junction thermal converter (SJTC) and a thin-film thermal converter (TFMJTC)

A thermal converter for high frequency is an example of the thermal converters for which the durability is improved. For the AC voltage standards of 1 MHz or above, for which the effect of impedance matching needs to be considered, it is desirable that a standard is calibrated by a 50 Ω thermal converter. Since the rated voltage of the conventional thermal converter is not sufficient, i.e., 0.5 V, thermal converters other than 50 Ω thermal converters are used for calibration. The voltage range of the newly-developed thermal converter is widened by five times from the rated voltage of the conventional thermal converter, owing to the adoption of the aluminum nitride substrate that releases heat of the heater. Figure 19[24] shows the voltage dependence of the AC-DC transfer difference of the thermal converter, whose heater resistance is 50 Ω, at the frequency ranging from 1 MHz to 100 MHz. As shown in the figure, the voltage dependence is very small. This thermal converter would not be broken even if 0.5 A voltage is applied in a short time period. This proves that the durability is significantly improved.

In the calibration rooms, the environment conditions including temperature and humidity are controlled appropriately. In the industrial operations, however, the temperature and humidity may not be kept sufficiently stable. In order to evaluate environmental resistance of the newly-developed thermal converter, the AC-DC transfer difference is measured in various temperature and humidity conditions. Figure 20 shows the results of measurement obtained when the temperature is varied in accordance with the IEC standards. The AC-DC transfer difference of the thin-film thermal converter remains unchanged within the range of detection sensitivity when the temperature is varied. The same measurement is performed at the ambient temperature of 15 °C. It is found that temperature dependence of the AC-DC transfer difference at the temperature between 15 °C to 35 °C is 1 ppm or below.[25] In order to demonstrate the stability against the humidity fluctuation, the humidity characteristics are evaluated in accordance with the IEC standards. Figure 21[25] shows the humidity characteristics evaluated and the relative humidity measured in the humidistat bath. The rate of change of the AC-DC transfer difference in the humidity test is 1 ppm or below as shown in Fig. 21. Based on the results, it is considered that the thin-film thermal converter

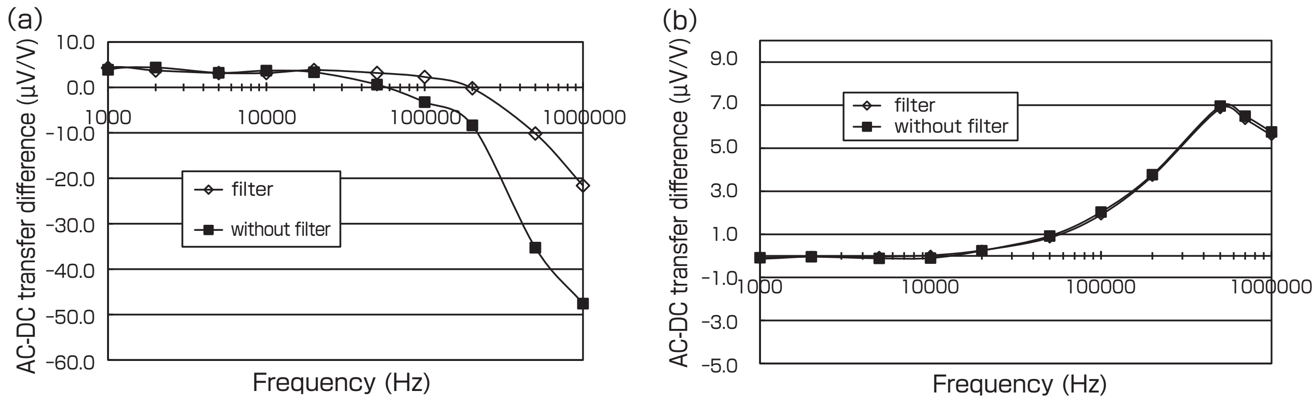

Fig. 18 High frequency characteristics of a multi-junction thermal converter
With a low-pass filter used (◆) and without a low-pass filter used (■) in the thermocouple output
(a) Measurement results for a conventional thermal converter in which thermocouples are located along the heater line
(b) Measurement results for the new thin-film thermal converter

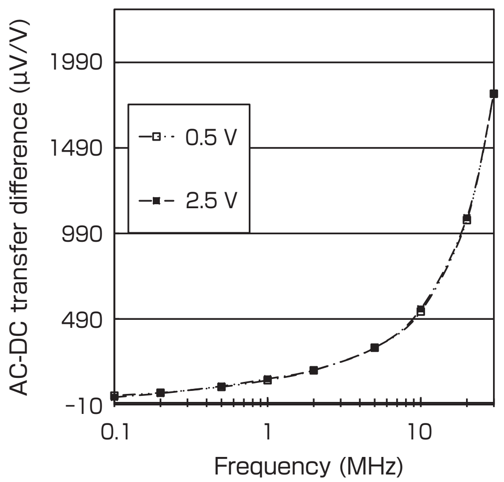

Fig. 19 Voltage dependence of a thin-film thermal converter with a heater resistance of 50 Ω

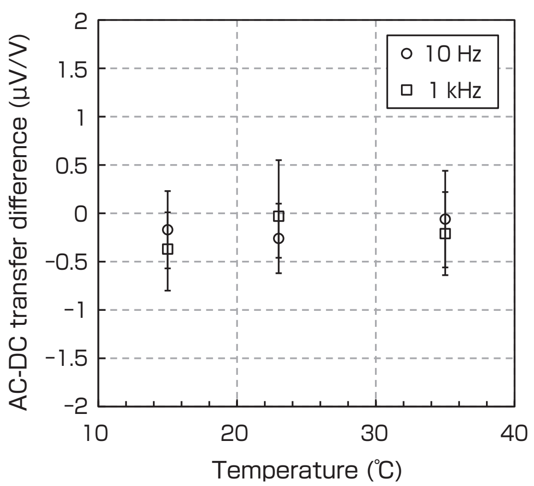

Fig. 20 Temperature characteristics of a thin-film thermal converter

Table 2. Comparison of the thermal converters

AC-DC converter	Single junction thermal converter	Thin-film multi-junction thermal converter	New thin-film multi-junction thermal converter
Fabrication method	Fabricated one by one manually	Microfabrication	Microfabrication
Structure	A heater and thermocouples are vacuum-sealed in a glass in three dimensions.	A heater and thermocouples are mounted on the same substrate	A heater and thermocouples can be fabricated independently on separate substrates
[Features]			
Heater resistance	25 Ω , 90 Ω	90 Ω	1 to 2000 Ω
Rated current	10 mA	10 mA	200 mA
Number of thermocouples	1pair	100 pairs	68 pairs
Resistance of thermocouples	8 Ω	10 kΩ	400 Ω
Output voltage	7 mV	80 mV	35 mV
Time constant	0.3 s	2 s	2 s
Temperature coefficient of heater resistance	10 ppm	10 ppm	5 ppm
Insulation resistance between heater and thermocouples @ 1 MHz	High	Low	High
Low frequency characteristics @ 10 Hz	Up to10 ppm	< 1 ppm	< 1 ppm
Thermal AC-DC transfer difference	Up to 1 ppm	Up to 0.1 ppm	Up to 0.1 ppm
High frequency characteristics @1 MHz	> 10 ppm	> 10 ppm	< 10 ppm

is sufficiently stable against humidity fluctuation. As described in Reference 25, the newly-developed thermal converter remains very stable over time just like the conventional thermal converter. The new thermal converter is found suitable for industrial applications.

The comparison of the performance between the conventional thermal converter and the developed thermal converter is summarized in Table 2.

7 Future development and challenges of the AC voltage standard

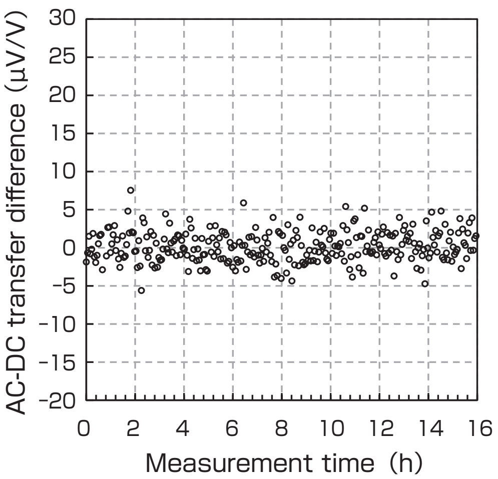

Fig. 21 Humidity characteristics of a thin-film thermal converter

The developed thermal converter is currently put into production at Nikkohm Co., Ltd. About 100 units are purchased annually and used by metrology institutes and/or calibration laboratories in 10 or more countries. The properties of thermal converters including conventional thermal converters are listed in Table 2. Our thermal converter is robust and durable since the rated current of the heater is improved dramatically. Meanwhile, bismuth and antimony are used for the thermocouple film and the melting point of bismuth is as low as 271.3 °C. Although the heater wire is improved so that large current can be applied, the result of the accelerated test shows that the thermocouple will be degraded after use over a long period of time.[26] At around 20 mA, the effect of heat generated by the heater is small and the thermal converter can be used continuously for at least 20 years. When larger current flows, however, the lifetime of the thermal converter will be 10 years or shorter due to degradation of the thermocouple. In the future, we will be working on improvement of the thermocouple so as to make the best use of the newly-developed thermal converter's characteristic, namely high tolerance to large current.

Although there is a demand from industry for the AC voltage standard in the low frequency region, the lowest frequency of the currently-available AC voltage standard is 4 Hz. In order to expand the range down to 0.1 Hz in the future, we are analyzing the thermal model of the developed thermal converter. A vacuum-sealed thermal converter is now under development, and we are to improve the low frequency characteristics further to expand the range.[27]

With respect to the future application of the thermal converter, National Metrology Institute of Australia is trying to apply our thermal converter not to the voltage standard but to the power standard.[28] The AC power standard is derived quantity composed of voltage, current and phase, but the power standard proposed by Australia is to be established based on the thermal converters. We are planning to improve uncertainties of the national primary standard[Term 2] by using the developed thermal converter in collaboration with Japan Electric Meters Inspection Cooperation, the Designated Institute (DI) which has established the power standard at commercial frequencies in Japan.

Another potential application of the thermal converter is development of a measuring instrument shown in Fig. 22 in which a variety of small detachable transfer standards are embedded. Since the thin-film thermal converter has realized downsizing and improved durability, it may be possibly used as the reference device for AC voltage measuring instruments. It will become possible to use high-precision AC voltage if the stable thermal converter is used as a reference for AC voltage values and the function to feedback the AC voltage output to the thermal converter is developed. By inserting multiple thermal converters, it also becomes possible to check the output values of a measuring instrument shown in Fig. 22. Development of such measuring instrument with built-in detachable transfer standards may lead to reduction of burdens to ensure traceability in the industrial operations. In general, calibration laboratories need to establish traceability for a variety of electrical standards such as DC voltage, DC current, AC voltage and current, resistance and so on. By removing one detachable transfer standard inserted in a measuring instrument and calibrating a single electrical quantity, there is no need to carry the whole measuring instrument. Thus, the calibration can be performed without affecting measurement of other quantities of electricity. By using this approach of calibration, we will promote use of the electricity standards with higher precision.

Acknowledgements

We would like to express our sincere gratitude to all those at Nikkohm Co., Ltd. for their outstanding contribution to productization based on our study.

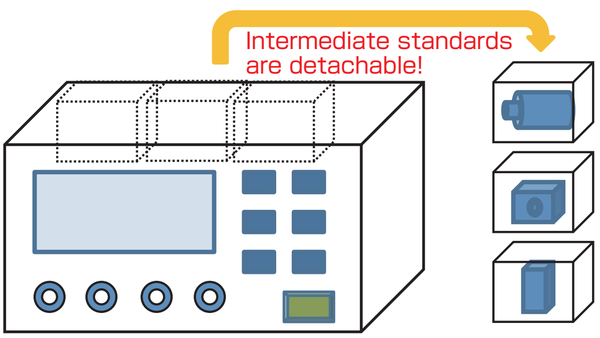

Fig. 22 Development of a measuring instrument in which detachable transfer standards are embedded

Terminologies

Term 1. Upper-tier reference standard : The traceability system is formed as a hierarchical framework covering the national metrology institute to industrial operations. The system consists of the national standards (primary standards) at the top, the secondary standards owned by the calibration laboratories that are calibrated by the national standards, the working standards owned by the calibration laboratories that are calibrated by the secondary standards and the measuring instruments owned by general users in industry that are calibrated by the working standards. The reference standard with which the reference value is provided is called "the upper-tier reference standard."

Term 2. National primary standard : The reference standards that are stipulated in the Measurement Act in Japan are called "the national primary standards." Standards calibrated by the national primary standards are called "secondary standards" in the framework of the Measurement Act in Japan.

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Discussions with Reviewers

1 General Comment

Comment (Mitsuru Tanaka, AIST)

In view of the gist of this paper, the technology, structure, and method are described fully in detail from the societal, industrial, and international perspective of the standard provision system.

In terms of understandability, however, the distinctions between the intended measures for the national standards and those for the calibration technique in industry are not yet explained clearly enough. It is necessary to give explanation on the measures relevant to these issues.

Answer (Hiroyuki Fujiki)

The goal of this research is to establish the domestic traceability system for the AC voltage standard, and it is required to deal with the national standards and develop the calibration technique in industry to achieve such a goal as you pointed out. We prepared the first draft having employment of the AC quantum standard and the AC-DC transfer standard as the national standards in mind. The AC quantum standard is mainly for the national standards, while the thermal converter takes care of both the national standards and the calibration technique in industry. As a result, their respective issues were mixed in the text. We reviewed the structure of Chapter 4 and revised it to describe the issues on measures for the national standards and for the calibration technique in industry separately in the independent subchapters. We believe that it is now easier to understand that “establishment of the national standards” + “development of new standard instruments” + “development of technique to promote usage” are essential for the establishment of the AC voltage standard system. In addition, with respect to the necessity of development of the thermal converter, we added the description that the thermal converter was required for the expansion of range of the national standards and using the thermal converter as a calibration instrument was useful for the provision of the AC voltage standard instead of using an AC voltmeter as a transfer standard. We also reviewed the description in Table 1 that listed the technical issues so that it is easier to distinguish the required techniques as the national standards and the techniques required for provision of the standards to industry.

2 Setting of the scenario where this thesis should be covered

Comment (Mitsuru Tanaka)

In Chapter 4, the author mentioned in the original version that “The range of the AC-DC transfer standards in Japan is being expanded starting 2001 in order to cover the range of international mutual recognition and requests from the industrial community.” This sentence suggests that the traceability system has not been completely organized by 2015 when this paper is to be printed. Please check if this interpretation is correct.

In Chapter 4 it is written that “The developed thermal converter is currently put into production by Nikkohm Co., Ltd. About 100 units are purchased annually and used by standards organizations in 10 or more countries. For continuous use in the future, we are working on further improvement in performances of the thermal converters.” I’m afraid that the description misleads some readers into believing that standard organizations are not satisfied with the performance. Therefore, why don't you distinguish between the scenario for this research and development and plans for future development?

Answer (Hiroyuki Fujiki)

The author completed updating the Measurement Standards Development Program at NMIJ set in 2001. The calibration services for AC-DC transfer standards provided by NMIJ cover the range international industries required. On the other hand, domestic industries request the extension of the frequency range below 10 Hz, where the AC voltage standard has not been sufficiently provided. So the authors revised the sentence based on your comment.

The biggest feature of our thermal converter is that the rated current increases dramatically compared with a conventional thermal converter. However, heat generation from high current affects the materials used for the thermocouples, which do not deteriorate by the low heat generated by the conventional heater. The new thermal converter we developed can be fully used as a national standard, however, we have a plan to improve the performance of the thermocouples to take advantage of the high rated current of the heater. The authors revised the section related to this issue to clarify this point.

3 Contents of technological elements for development of thermal converters

Comment (Mitsuru Tanaka)

It is noteworthy that the description of advantages and disadvantages of technological elements for the development of thermal converters are included. However, some of the candidate elemental technologies lack sufficient explanations. I am not denying the ones that you actually adopted as part of the overall configuration method, but it would be appropriate to add more description from the perspective of objectivity.

Answer (Hiroyuki Fujiki)

Detailed descriptions on the wired multi-thermocouple thermal converter and the thermal semiconductor RMS sensor, which are now provided in Chapter 3 as the candidate elemental technologies for development of the thermal converter, were omitted in the initial draft. The goal of this paper is to establish the domestic tractability system for the AC voltage standard, and we aimed to develop a thermal converter that can satisfy both the development of the national standards and technique to promote its usage. Therefore, we only introduced the names of the wired multi-thermocouple thermal converter that is only specialized for the national standard instrument and the thermal semiconductor RMS sensor that is specialized for the calibration instrument for the standard provision, to avoid even more lengthy description. Considering that explanation of each candidate elemental technology can help general readers other than experts understand better, we added the details on the above candidate elemental technologies.

4 Improvement of the description for product realization

Comment (Hiroaki Hatori, AIST)

As a whole, the description from the background to the scenario of the research and development is very thorough (although it seems rather redundant). However, it may be hard to understand for non-expert readers since the part from the actual development to commercialization is somewhat written in an itemized form and the provided technological development elements are relatively many.

Answer (Hiroyuki Fujiki)

With respect to the technical development elements of the thermal converter, we only introduced the technology briefly so that this would not be like a specialized academic paper. As for the commercialization, the conventional thermal converter has not been used widely in the calibration labs that are close to the production sites because mass production is difficult due to high level of difficulties in the fabrication techniques and it is destroyed easily by operation error including overcurrent. We considered that for commercialization, it was important that the thermal converter had the performance that allowed it to be used as the national standard as well as improved durability and usability. In the initial draft, we provided the technological elements that are required for development of the relevant thermal converter in the subchapters of the elemental technologies for development and Table 1, but in retrospect, we realized that the explanation was insufficient in some parts. We reviewed the section regarding the development of the thermal converter and added the explanation of each elemental technology and details on the corresponding efforts to solve the issues. As for the explanation of each technological element, we revised the text and Table 1 while adding figures and tables based on the questions and comments from reviewers.

5 Efficient arrangement of the contents for technological elements of thermal converters

Comment (Hiroaki Hatori)

The goals, indices, and reasons for the development of the thermal converter are listed in Table 1 for the technological elements. Meanwhile the background of development and the features of the actually developed thin-film thermal converter are described in Chapters 5 and 6 respectively. Thus the technological elements seemed to be scattered over various areas and it may cause confusion for readers. From a synthesiological perspective, it is important to organize and clearly describe the important technological elements that led to commercialization and the background of development. I would suggest summarizing the main points of the actual development and the resulting features in a figure or a table.

Answer (Hiroyuki Fujiki)

Our motive for the development of the thermal converter was the existing state where although a high-performance thermal converter was required for expansion of the provision range of the national standards for the AC voltage and improvement of uncertainty, it was difficult to acquire a high quality thermal converter. We also considered that a new standard measurement instrument had to be developed for dissemination of the AC voltage standard because different calibration instruments were used for the AC voltage standard and the AC-DC transfer standard. During the development of the thermal converter, its features are determined according to the combination of various elemental technologies. As a result, descriptions of each elemental technology were scattered in the initial draft and the paper was not easy to read for readers other than experts. We reviewed the structure of the text in order to organize the background of development and the major technological elements; we packed the meaning of the development of a new thermal converter in Chapter 4, and moved the elemental technologies which were in Chapter 4 to Chapter 5. With respect to the major technological elements in Table 1, we revised and added to the table and the text so that the details and reasons for development were connected to the background of development. In addition, we prepared Table 2 to enable comparison between the features of the conventional thermal converter and the developed thermal converter, and added the figure numbers that were relevant to the major elemental technologies to Table 1.

Green photonics for laser-based manufacturing

— Photonics contributes to a sustainable society in the "photon century" —

Hiroyuki Niino

[Translation from *Synthesiology*, Vol.8, No.3, p.145-157 (2015)]

Green photonics is expected to reduce energy consumption and pollution associated with a broad range of manufacturing processes. This paper is a study on the development of laser-based methods and their applications. High precision surface processing of various materials is a key technology for practical industrial applications. Well-defined micro-fabrication with high-speed and high-quality treatment of materials was performed by laser irradiation. The technical challenges are particularly great in this area, but recent developments in laser processing have opened up new frontiers. Due to advances in laser processing systems, and greater understanding of the phenomenon of diverse excited states generated by laser irradiation, these methods can be considered mature and versatile techniques that present some key benefits over other more established fabrication techniques.

Keywords **:** High-power laser, laser-material interaction, photo-induced excitation, surface chemical reaction

1 Introduction

The clarification of interaction between photon and matter substances and photon (light) has been an important academic research topic since ancient times, and currently, research is promoted actively as an advanced topic in many countries. Looking at the process of photon absorption by substances, various excitation states are induced in substances (atoms and molecules) through photon absorption, followed by a relaxation process, chemical bond cleavage, and others. In the relaxation process from high-vibrational excitation, a high-temperature state occurs through the so-called photothermal process, and in the chemical bond cleavage from an electron excitation state, the chemical reactions such as dissociation of molecules and recombination of chemical bonds occur through the photochemical process. The main characteristic in practical use is that area-selective localized treatment to a specific area is possible by irradiating the base material with light focused into micro-patterns or micro-spotlights.

The main topic of this paper is the processing technology using lasers, and the localized laser treatment technology based on the characteristic photo-excitation process induced by irradiating high-power lasers to various advanced materials including polymers, glass and ceramic, metals, and composites is addressed. The goal is to use the laser excitation processing technology for cost reduction, increased efficiency, and environmental load reduction in industrial application, by promoting process and part saving in manufacturing. Particularly, we aim for widespread use in society by improving energy-saving characteristics of products, by providing novel members, parts, and products through the realization of high-precision, high-quality processing of difficult-to-process materials. By introducing the laser technology to the manufacturing process, we hope to achieve greening of the product and manufacturing processes.

The greening of the manufacturing process means the promotion of energy saving, material saving, and waste reduction throughout the whole process of new manufacturing methods compared to the conventional methods. Since the energy saving measures are thoroughly implemented in the Japanese factories, expectation is high for altering the process content such as process saving and reduction in the number of parts rather than simple renewal of a process. Greening of the products means that the production volume of energy-saving members and parts that are desired by the market are stabilized and used in products. Although the effect may be small for a single part, the ripple effect on society as a whole may be large if the amount used throughout the market is enormous. Particularly, if such parts are used as main parts of durable consumer goods, the energy-saving effect will be enhanced.

For the R&D of material processing technology using lasers in Japan, budgets are allotted heavily by the New Energy and Industrial Technology Development Organization (NEDO) of the Ministry of Economy, Trade and Industry (METI), and the Japan Science and Technology Agency (JST) of the Ministry of Education, Culture, Sports, Science and Technology (MEXT), for industry-academia collaboration toward industrial application. Overseas, the collaboration

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for photonic application technology is encouraged by the European Union and the European governments. In the United States, the National Additive Manufacturing Innovation Institute (NAMII) was established in 2012 as an industry-government-academia collaboration center, and research for 3D forming technology is being promoted.

In Chapter 2, the characteristics of the laser processing technology are compared with the competing technologies, and the capabilities as of present are overviewed and organized. In Chapter 3, what kind of elemental technologies were combined for the processing technology using lasers are presented by describing the specific case studies of actual research that we conducted. In Chapter 4, the significance of research results and the comparison and discussion with the future scenario are discussed.

The year 2015 when this paper is published was designated and declared as the “International Year of Light (IYL2015)” at the United Nation General Assembly (UNGA 68, Paris) (Fig. 1). Various educational activities are planned to feature the importance and attractiveness of the science and technology of light.[1]

2 Characteristics of the laser materials processing technology

2.1 Main properties of laser devices and their effects

Since the laser has higher temporal and spatial coherency compared to other light sources, it has the characteristics of: (1) monochromaticity (short wavelength, wavelength selectivity), (2) high directivity, and (3) high intensity. Table 1 shows a list of properties of the laser devices currently used in laser processing. Main properties are the five parameters: laser wavelength, average power, pulse width, pulse repetition rate, and beam quality. Wide ranges of property distribution have been achieved for each parameter. However,

Fig. 1 Official logo of the International Year or Light (IYL2015; color version)

Table 1. Specifications of laser equipment used in materials processing

Main property	Specifications
Laser wavelength	IR, Visible, UV, VUV, X-ray; 800 nm, 400 nm, 200 nm, 10 nm (⟷)
Average power	1 µW, 1 mW, 1 W, 1 kW, 100 kW (⟷)
Pulse width (sec)	cw, ms, µs, ns, ps, fs (⟷)
Pulse repetition rate	10 Hz, 1 kHz, 100 kHz, 1 MHz, 1 GHz (⟷)
Beam quality	Multimode, Single-mode (⟷)

Note) Although the performance of laser equipment is evolving constantly, the specifications shown in the table have not been comprehensively or entirely realized between the main properties.

the characteristics of lasers that can be emitted from one laser device is limited, and the selection of the device appropriate for the use objective and the optimization of irradiation parameters are important tasks in conducting high-speed, high-quality laser processing. Another characteristic of laser irradiation is that the irradiation environment factors such as temperature and gas can be selected freely.[2]-[4]

In the fundamental step of laser processing, the absorption of photon energy to the target material without loss is important. By irradiating photons that possess wavelength (number of vibrations) that corresponds to the energy difference between the quantum state of substances, it is possible to shift to excitation level (it is also necessary to fulfill the selection principle). If the excitation can be achieved with the absorption of one photon, it is a one-photon absorption process (linear absorption process) that is a phenomenon that occurs commonly in nature. The absorption spectrum that is measured using an ordinary spectrometer shows wavelength dependency of photon absorption volume in one-photon absorption. Therefore, in order to infuse photon energy to the target material without loss through one-photon absorption, the basic procedure is to irradiate at the absorption band wavelength of the material.

On the other hand, if the density of light is increased, the phenomenon in which multiple photons are absorbed simultaneously to a substance is observed. This is called the multi-photon absorption process. Since it occurs in proportion to the power of light intensity (nonlinear absorption process), it is a phenomenon that occurs prominently in the irradiation of ultra-short pulse lasers with high peak power of femtosecond- or picosecond- pulsed light. The level excited by multi-photon absorption is the sum of photon energy that is absorbed simultaneously, and the excitation to levels higher than the one-photon absorption is possible. That is, with the multi-photon excitation of near-infrared region with wavelength of 1,000 nm, the excitation level can be shifted to the level equivalent to the energy of visible or ultraviolet energy. There are many organic polymer materials and glass materials that

Table 2. Historic transition of high-power laser equipment used in material processing

Materials processing	Technological transition of laser devices (1980 1990 2000 2010 2020)
Macro-processing ・Sheet metal cutting ・3D fabrication	CO_2 gas laser → YAG laser → Fiber laser → Semiconductor laser →
Micro-processing ・LSI lithography ・Microfabrication of transparent materials	Excimer laser → 2nd and 3rd harmonic laser → Femtosecond laser → Picosecond laser →

Note) Left end of a device sign corresponds to the "year when it was put to industrial practical use."

possess strong absorption bands in the ultraviolet to visible region but have no absorption bands in the near-infrared region. The irradiation method, where the multi-photon excitation is induced only in the area inside the base material where the light is focused by irradiation with near-infrared ultra-short pulse lasers, is being studied.[5]

Average power is the total sum of photon energy emitted by a light source device in one second. With pulse action oscillators, the average power is the product of photon energy and pulse repetition rate of a single pulse. The average power is the factor that determines the rate of the whole processing, and a light source device with large average power output is selected for the application fields that demand high-speed processing.

For beam quality, in the case where the energy intensity in the radial direction of the laser shows Gaussian distribution is called the single mode, and smaller focused beam diameter can be obtained compared to the multimode light. Therefore, in the case where irradiation is done by a single spotlight, high-speed scanning by the single mode is effective. However, for LSI (semiconductor) lithography where fine, complicated patterns are transferred to the photoresist, the multimode light with narrow-short bandwidth that is capable of controlling the speckle noise (spots of light and dark that can be seen in scattered light; a unique phenomenon that occurs when the laser is coherent) is used as the light source of the reduction optical system. It is effective to use lasers when one wishes to conduct site-selective processing or analysis of specific areas. Moreover, a pulsed laser device improves temporal control in addition to the aforementioned characteristics. Therefore, it becomes possible to precisely handle the two control factors, "space" and "time," and this enables material control technology in the micro- and nano-scale region.

Table 2 shows the historic transition of high-power laser equipment for material processing. In the recent progress of laser equipment, the improvement of high power, beam quality, and achievement of short pulses are points that are gathering attention. With fiber lasers that are being introduced to the market at speed similar to CO_2 gas lasers and YAG lasers that used to lead the microfabrication fields, the average power improved up to the 100 kW range, and the electricity-light conversion efficiency reaches 30 % for the plugin and thus have high energy-saving performance. This is mainly due to the high performance of the laser diode device, and the achievement of high power (several kW range) is also remarkable in the stacking laser diode device for direct irradiation. These laser devices have realized high-quality, high-speed processing in various material processing technologies including cutting, drilling, welding, joining, surface modification, and 3D fabrication. The short wavelength lasers and ultra-short pulse lasers are being introduced in the field of microfabrication.

2.2 Characteristic of the laser processing machine system

The industrial machine system for laser processing technology in manufacturing lines consists of four main elements: (1) the laser device, (2) the optical and beam delivery system, (3) the positioning and transfer system for materials (products), and (4) the processing procedure (including in-process monitoring technology). The core elemental technologies that determine the processing performance are (1) and (4). The elemental technologies that improve the productivity in manufacturing are (2) and (3). As actual machining tools, not only the 2D processing devices for flat base materials, but also the 3D processing systems that can handle 3D products is being developed for use in the manufacturing line. The technology that allows the precise reflection of digital design data to processed products is advancing and continues to evolve.

The progress in irradiation optical systems and transfer systems is contributing to the increased processing resolution and processing speed, as well as increased size of the products. As a characteristic example, laser processing is applied to the manufacturing process of liquid crystal display television (LCD-TV) and photovoltaic cells. In the LCD-TV, a repair machine system that saves the defective lot during panel manufacture by correcting the defect of the TFT array to increase the yield has been developed, and in the photovoltaic cells, the patterning machine system for various thin films such as transparent electrode films, semiconductor films, and metal films are used. As the size of mother-glass plates increases every year to several meter levels, the processing precision of micrometer level is demanded. The dynamic range may reach five to six digits, and state-of-art mechatronics technology is utilized.

Recently, the advanced technology for automatic control among various elements, where the sensors attached to various main elements described above possess internal communication functions to exchange information mutually, is being developed in conjunction to the progress in IT and robot technologies. It is expected to shorten the manufacturing tact time and increase the operation rate of the whole plant, and efforts such as IoT (Internet of Things) in the United States and Industry 4.0 of Germany are gaining attention.[6][7] In the IoT for manufacturing industry, it is expected that not only advancement and optimization of the manufacturing process but also a globally dense manufacturing system can be constructed by directly linking the customer demand and ordering information. Industry 4.0 is almost the same concept as IoT, and the name denotes the "Fourth Industrial Revolution" in human history.

2.3 Comparison with the competing processing technologies

2.3.1 Processing by physical mechanisms such as cutting and drilling processes

Compared to competing machining technologies, since laser processing is noncontact processing that does not employ cutting tools, there is no expendable parts by wear and degradation. Also, since there is no process reaction force, high-precision processing can be conducted on base materials with low stiffness. Transmission loss is small, and the light source device does not generate noise or vibration. Even with continuous wave lasers of kW range, transmission is possible from the light source device to the processing head using optical fiber delivery. The connection of the light source and the head is simple, and there are advancements in cutting and welding technologies by remote processing (method whereby the processor head and base materials are kept at a distance) that can be applied to high-speed processing in remote or tight areas. When conducting laser processing by physical mechanisms, the mechanism is often based on the generation of high-temperature conditions through the photothermal excitation. Therefore, a major characteristic is that the balance of light energy absorption and the rate of heat diffusion are optimized, assist gas is used, and this can be applied to the processing of metal materials with high melting points. In laser processing, effective processing can be done for target materials up to several centimeters, but currently, cutting of plates with thickness of 5 cm or more is difficult.

Laser processing technology is expanding application as a technology for medium to small volume production. In the processing using molds, work efficiency and profitability are expected for mass-production for lots in several tens or several hundreds of thousand units, while laser processing may be a cost reduction technology for production of several hundred to several thousand units in the prototype development stage. By conducting flexible processing by direct laser drawing, the necessity of mold fabrication and the risk factors such as mold management are removed, and it is being used widely as the production technology for high-precision processing that allows quick delivery (shortened delivery time) and flexible changes in specs for small to medium volume production of multiple product types.

2.3.2 Processing by chemical mechanisms such as photochemical surface modification

When chemical bond cleavage from an electron excitation state by photo-irradiation is applied, it is possible to induce chemical reactions such as molecule dissociation and chemical bond recombination with high efficiency and at high density. If micro-focused beam or micro-patterns of the light is irradiated onto target materials, the area-selective localized chemical treatment to specific areas can be done easily. Not only can the form of the target material be modified by physical laser processing, but also arbitrary changes in the chemical surface property can be done. The characteristics of surface modification using light are as follows:

- direct formation of modified layer on the material, micro-pattern modification,
- reduction of consumption of reagents, process without solvents, and
- treatment in air or under atmospheric pressure.

It is possible to induce photoreaction by using a lamp as a light source device. The merits of using lasers are that pattern forming treatment is possible and that active species can be generated at high density. For the surface modification of materials, there are four main methods of laser irradiation as shown in Fig. 2. Figure 2(a) is a method in which lasers are irradiated directly onto a material that one wishes to modify. If photoreactive molecules or functional groups are present in the substrate or surface layer, the molecules or functional groups in the surface layer are excited by laser irradiation, and this kicks off a surface reaction. By carefully selecting the type of photoreaction induced, it is possible to add a functional group to the surface, and set off polymerization or alter the surface polarity. By coating the substrate surface

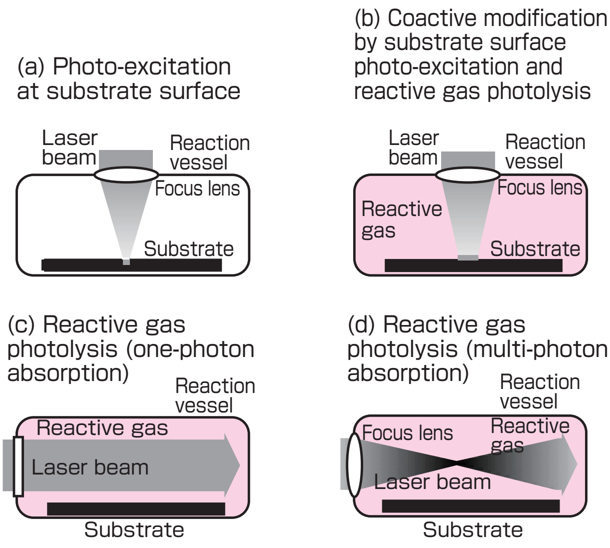


Fig. 2 Surface modification method by laser processing

Table 3. Industrial applications of surface modification achieved by photoreaction

Type of surface modification	Industrial application
Improvement of wettability	Improvement of affinity and adhesivity, printability, improvement of biocompatibility, water repellency, antifogging
Cross-linking, crystallization	Formation of hard surface layer, wear resistance
Removal of contaminated layer	Surface cleaning
Surface modification (grafting, coating)	Formation of highly lubricant layer, formation of colored layer, photo-reflective (prevention) film, liquid crystal oriented film, heat resistance, chemical resistance, gas barrier property, antistaticity, weather resistance, flame resistance

with a thin hydrophilic or hydrophobic layer, and then partially exposing the substrate by removing the film layer by laser processing, it is possible to form micro-patterns using the surface property.

Figure 2(b) is the derivative of Fig. 2(a), and reactive gas is used as the atmosphere for laser irradiation. Therefore, it is possible to accelerate the surface reaction, and to conduct a target surface reaction by selecting the optimal reactive gas type without intentionally introducing the photoreactive molecules to the substrate surface layer. In this method, it is also possible to photo-excite both the substrate and the reactive gas, and patterned surface modification can be done as in Fig. 2(a).

In Fig. 2(c) and 2(d), the characteristic is that surface modification properties are obtained without photo-excitation of the substrate, but by the deposition of the photoreactive product of reactive gas on the substrate surface. In the case where the reactive gas is dissolved by one-photon absorption, the normal incidence irradiation as in Fig. 2(c) is sufficient. In the case where the reactivity of gas molecules is low, or if multi-photon absorption is necessary, practical reaction efficiency can be increased by tightly focusing the lasers inside the reaction vessel.

Table 3 shows the major types of surface modification and application examples mainly for photoreaction. In order to fabricate a modified surface with low time degradation and with high durability, more often, it is better to modify not just the uppermost surface layer of the material of the reaction site but also the internal layer to a degree base material characteristics are not lost. Particularly, in systems where the main chain structures of molecules are flexible and subject to movement like in polymer materials, the surface hydrophilicity may gradually decrease after treatment since the hydrophilic group in the uppermost surface layer may diffuse into the internal layers. Therefore, highly durable modification can be achieved by adding hydrophilicity to the surface layer of about 1 µm thickness.

3 Specific case studies

In Chapter 3, three specific case studies are presented that aimed at further application and practical use of methods described in Chapter 2 using the current laser processing device system as base technology. All the cases are high-speed, high-quality processing that is difficult to achieve using ordinary laser processing methods or other competing processing technologies.

3.1 High-speed, high-quality processing of composite materials

Recently, CO_2 reduction and energy savings are promoted as measures against global warming, and weight reduction and decreased fuel consumption of transportation machines such as automobiles and aircraft are progressing. Carbon fiber reinforced plastic (CFRP) that has superior specific strength and specific elasticity compared to metals such as aluminum is given as a major candidate structural material for weight reduction. In the transportation equipment, the CO_2 reduction effect of automobiles and aircraft that use CFRP is drawing interest, and the wide diffusion of products developed using such materials will be an effective way to promote energy savings of society as a whole. However, CFRP is known as a dissimilar difficult-to-cut material, and the development of high-precision cutting and joining technologies are demanded as innovative manufacturing technology. Moreover, further shortening of the manufacturing tact time is an urgent issue. When considering application to industrial manufacturing processes, the target-processing rate can be set from the value of tact time resulting from the manufacturing lead time. Taking the example of mass-production of passenger vehicles, the tact time is approximately one minute. Therefore, the processing speed of about 6 m/min is necessary for the exterior trimming of roof and hood that are large parts, based on the processing area needed for the size of the individual parts. Therefore, we studied the industrial application of high-speed laser processing to CFRP materials (Fig. 3).[8]

To compare with laser processing, the processing speed

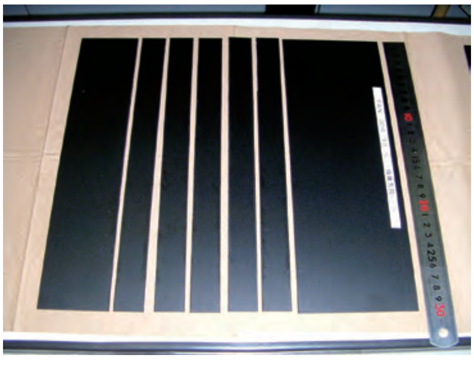


Fig. 3 Laser cutting of 30 cm square CFRP substrate

of water jet processing and mechanical machining that are positioned as competing technologies actually used in aircraft manufacturing were measured using the 2 mm thick CFRP material. The results were 0.1 m/min and 1 m/min, respectively. For the aforementioned objectives, these processing methods lack speed, and issues such as tool wear and parts degradation occur. In case of laser processing, if the demand is for improved speed only, the problem will be basically solved by increasing the average power of the oscillator, and the processing speed of several m/min can be achieved by large laser devices with kW range average power. As a technological issue to be overcome, the important point is to control the reduction of heat damaged area during the processing.

Carbon fiber is a material made of fibers of 5~10 micron diameter with high heat resistance and high thermal conductivity. In contrast, resin is a matrix material with low heat resistance and low thermal conductivity. CFRP has a structure that is composed of the two materials, and in the case where excess heat input is generated during high-power laser irradiation, there is a tendency for heat damage and delamination of the resin part. Particularly, in the case of continuous fiber CFRP materials, the carbon fiber bundles may act as heat conduction paths, and there is a possibility that the heat damage may spread to the resin area around the process site. If the degree of adhesion between the fiber surface and the resin interface decreases due to heat damage, the strength property of the structural material declines, and it is necessary to avoid as much as possible the spread of heat damage around the process site. For example, it was found that if a CO_2 gas laser (800 W, 20 kHz, 8 μs) is used in standard cutting conditions for sheet metal, the heat damage of the resin layer spreads over 1 mm in the cross section of a 2 mm thick sample. This is an inappropriate condition setting. Therefore, a high-speed sweep method was used to conduct multiple irradiation (multiline multipath irradiation) along the processing line, and the number of irradiation needed to completely cut a 3 mm thick base plate was greatly reduced. For the heat damage to the resin layer, it was found from the micro X-ray CT measurement that it was kept to about 0.1 mm (Fig. 4). The development of the domestic high-power fiber laser device was done as an industry-academia-government collaboration, and as of now, the processing speed of 6 m/min has been attained (Fig. 5).

3.2 Localized surface chemical reaction of the resin surface

For the surface modification of polymer materials, research for the improvement of wettability and adhesiveness is being done actively, and it involves important technologies in basic research as well as in wide-ranging fields of industrial application. In the polymer materials that mainly consist of hydrocarbon chains such as polyimide and polyester, hydrophilicity can be gained by replacing hydrogen with the hydrophilic group in the carbon-hydrogen (C-H) bond sites. Therefore, a photo-oxidation reaction is the general method of modification. The point of treatment to attain hydrophilicity in polymer materials is to introduce the hydrophilic group to the side chain structure site without breaking the main carbon chain structure. If the main carbon chain structure is broken by oxidation, the molecular chain becomes low-molecular weight, and this may cause elution, thus becoming a factor that lowers durability. In this subchapter, chemical surface modification using lasers is explained through the example of obtaining surface hydrophilicity in fluororesin.

Fluororesin represented by polytetrafluoroethylene (PTFE) is an excellent material with high chemical stability and heat resistance (Fig. 6). However, since it has very high hydrophobicity on the surface, adhesiveness and bonding property with different materials are extremely poor, and currently, the surface is made hydrophilic by defluorination through immersing the PTFE specimen in a metallic sodium organic solution. The organic solution of metallic sodium has the danger of ignition and degrades rapidly. Moreover, since the specimen is immersed in the solution, the whole surface is modified, and the development of a new method that is safe

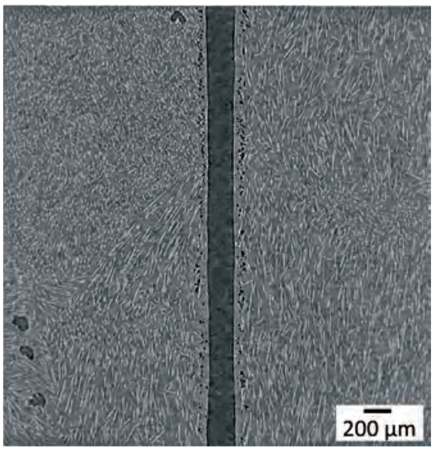


Fig. 4 Cross-sectional picture of micro-X-ray CT of CFRP sample after laser cutting[8]

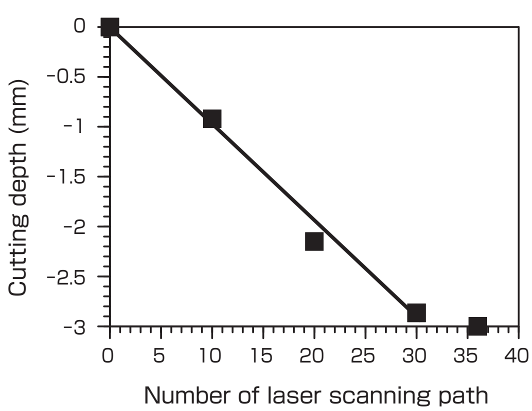


Fig. 5 Cutting depth of 3 mm thick CFRP sample using double-line multipath laser irradiation
(Laser beam scanning speed of 3.6 m/s)

and allows area-selective modification was awaited.

The characteristic of the surface modification of fluororesin is that the hydrophilicity is attained by breaking the carbon-fluorine (C-F) bond of the side chain and replacing the fluorine atoms with hydrophilic groups. However, since the C-F bond has higher chemical bond energy than the C-C bond of the main chain, the main chain C-C bond will be broken unless a reaction system that acts specifically on the C-F chain is selected, and surface etching will occur due to the detachment of the monomer unit and the decreased molecular weight of the polymer chain. In the aforementioned metallic sodium organic solution, the key reaction is the reaction of sodium atoms and fluorine atoms to specifically generate NaF. Similarly, the method of directly photo-exciting polymers by laser irradiation causes the break in the main chain C-C bonds, and it is difficult to change the surface to hydrophilicity efficiently. Therefore, it is necessary to use the reaction system that acts on the C-F bonds by introducing the reactive gas as in Fig. 2(b). Here, we describe a case study using hydrazine.[9]-[11]

Hydrazine (N_2H_4) molecules are known to dissolve at high quantum efficiency by ultraviolet light irradiation. In the photolysis process, hydrogen atoms, hydrazyl radicals, amino radicals, and others are produced at high efficiency (Fig. 7). First, the hydrogen atoms react with fluorine atoms to produce HF (exothermic reaction), and the carbon radicals produced by the desorption of fluorine atoms react with the hydrogen atoms or amino radicals, and as a result, a modified surface with partial replacements by the amino group consisting mainly of hydrocarbon chains is obtained. In an actual experiment, as seen in Fig. 8, the hydrazine was introduced into the decompressed reaction vessel as steam and irradiated with ArF excimer lasers (wavelength 193 nm). In the X-ray photoelectron spectroscopy (XPS) measurement, the fluorine signal decreased significantly after the laser treatment and the nitrogen and oxygen peaks occurred. The atomic ratio was C:F:N:O = 100:1.6:19:3.3, and the majority of fluorine atoms were removed from the surface.[10] The contact angle to water was 130º→25º, and the surface became hydrophilic. From the results of the static secondary ion mass spectrometry (SIMS) or positive ion observation, it was clearly shown that the change to hydrocarbon chains occurred while maintaining the main carbon chain structure after the laser treatment (Fig. 9). Similar active species can be generated by plasma treatment, but the laser method is superior from the perspective of generation concentration and pattern treatment.

When ordinary chemical plating is done to laser treated substrates, nickel plates adhere only to the hydrophilicized parts (Fig. 10),[12] and the adhesivity was maximum100 kgf/cm^2

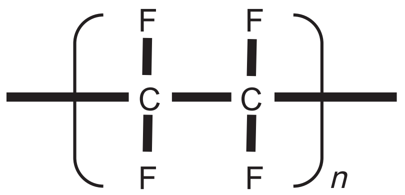


Fig. 6 Chemical structure of PTFE

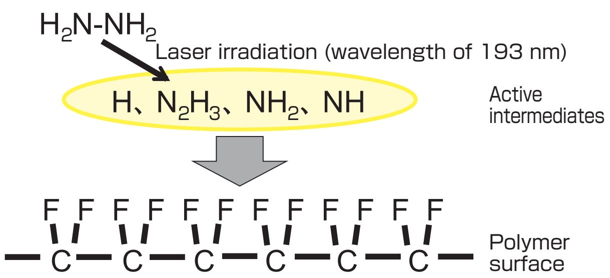


Fig. 7 Schematic diagram of the surface reaction

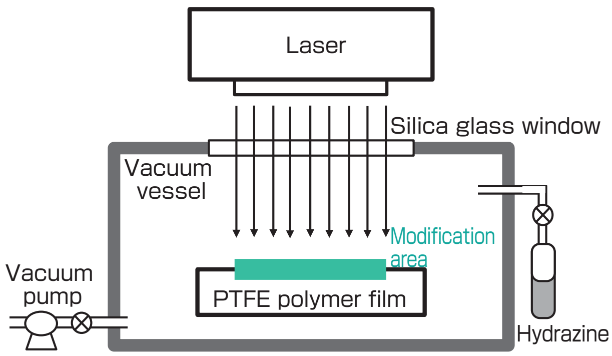
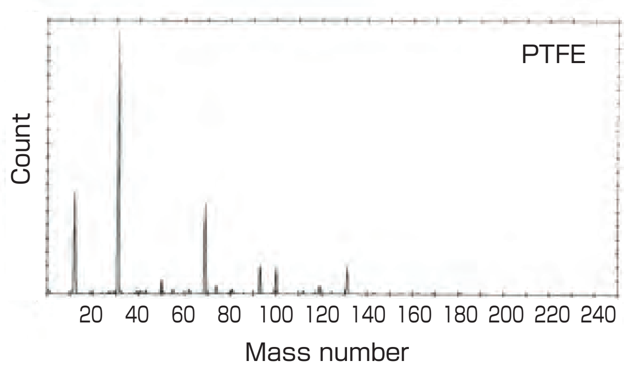


Fig. 8 Experimental apparatus



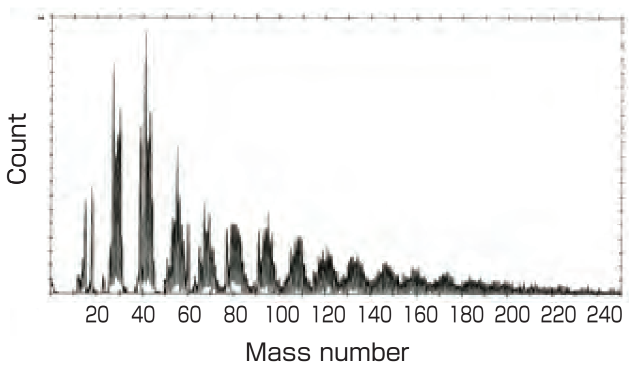


Fig. 9 SIMS spectrum of a polymer surface: left, before laser treatment; right, after laser treatment

in the pullout tension test.[10] When an iron rod and a fluororesin sample were joined using a cyanoacrylate adhesive, maximum 10 MPa tensile strength was obtained.[11] Considering that the tensile strength of fluororesin itself is about 10 MPa, it could be said that the modified layer adhered solidly to the base layer.

3.3 High-quality microfabrication of hard-brittle materials

In the case of base materials with extremely small or no laser absorption, the penetration length into the substrate becomes large since the excitation density is small. Therefore, damages such as cracks and chipping occur around the irradiated area during processing, and high-quality microfabrication becomes difficult in many cases. Such transparent materials include silica (quartz) glass and sapphire materials that have no absorption in the visible and ultraviolet ranges, and these are categorized as hard-brittle materials.

AIST developed its own laser processing method for indirectly microfabricating silica glass surfaces by ablation of dye solutions, where the ultraviolet lasers are irradiated, while a dye solution that readily absorbs ultraviolet light is placed in contact with the processing target.[13][14] Laser-induced backside wet etching (LIBWE) has two types: the excimer laser exposure projection-mask type that has high size precision, and the laser scanning irradiation type where the prototypes can be made easily (Fig. 11). In the LIBWE method, a highly concentrated dye solution is used, and lasers can penetrate only a few µm into the solution layer and is completely absorbed in this thin layer. Therefore, a high-density excitation state of dye molecules is formed locally near the silica interface, ablation of the solution occurs, and the silica glass surface layer is etched at depth of several tens of nm by excess high-temperature and high-pressure. The processing depth increases in proportion to the cumulative pulse number by conducting concurrent irradiation.[13] Compared to other methods, the photoresist protection layer formation and its removal, which were necessary in the conventional lithography process, as well as vacuum devices are not necessary, and the pretreatment and post-treatment are greatly simplified.

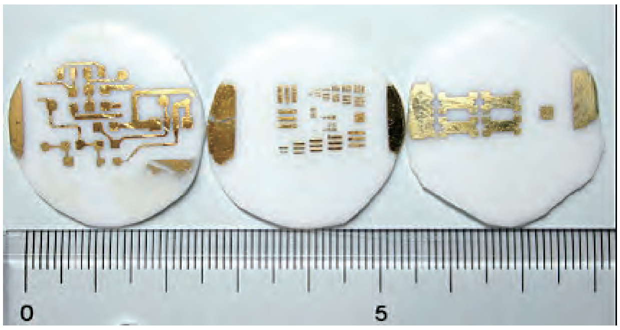


Fig. 10 Nickel chemical plating on PTFE (Topmost surface of plated film has been gold replaced.)[12]

The evenness of the processed surface is high, and adhesion of broken fragments that might occur during ablation and fine processing damages such as cracks were not observed. With the improvements of the projection-mask exposure optical system such as the installment of a beam homogenizer and a projection lens array, we succeeded in the lattice microfabrication with maximum of 1 µm resolution and microfabrication on large optical elements (Fig. 12).

The result of processing when aluminosilicate (SiO_2-Al_2O_3-Na_2O) glass was selected as the base material is shown in Fig. 13. Aluminosilicate glass has a thermal expansion property similar to silicon wafers, and since anodic bonding with little distortion can be formed with silicon, it is used widely as conjunction glass for micromachining to fabricate various sensors such as MEMS. Using the nanosecond pulse lasers with wavelength of 355 nm, laser beam scanning was done using the galvanometric optical scanner on the glass substrate in contact with the pyrene-toluene solution. The galvanometric optical scanner is an optical device that scans the laser at high speed and in a wide range using a motor and a reflective mirror, and it is appropriate for direct drawing along a designed diagram (vector mode scanning).

For three types of grooves of width 20 µm (single-line scanning), 50 µm (accumulation of four lines), and 80 µm (accumulation of eight lines), the depth of grooves

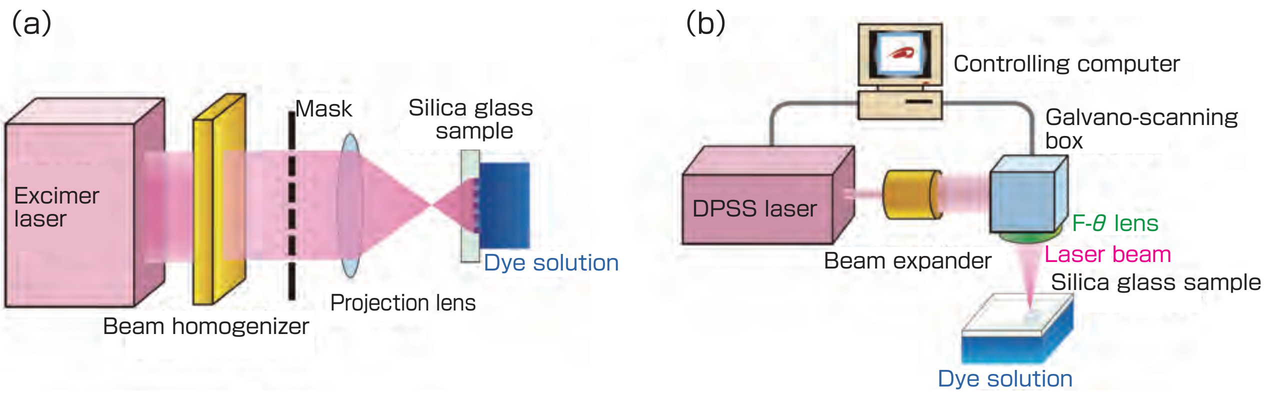


Fig. 11 Experimental apparatus for the LIBWE method
(a) Excimer laser exposure projection-mask type, (b) DPSS laser/ beam scanning irradiation type[14]

obtained by concurrent irradiation with increased number of processing paths was 150 µm or deeper for each groove. Figure 13 shows the deep groove structure with different depths and widths on one piece of glass substrate. In the LIBWE process, this can be fabricated in one batch, and this demonstrates the advantageous characteristic in reducing the number of processes.

4 Discussion: Meaning of the research result and comparison with the future scenario

Development progresses for innovative, lightweight, and high-strength materials that are aimed to achieve a sustainable and safe society. In considering clarification of research goals that one wishes to be realized in society, there is a need for a new processing technology that exceeds the conventional methods for the integration of materials and product realization. Achievement of high performance such as multiple functions, micro-sizing, and high speed is specifically demanded by companies. Therefore, the research goal here is to promote the greening of the manufacturing processes and products through material processing technology using lasers.

The future scenarios for the specific case studies presented in Chapter 3 for attaining this research goal and the means to achieve it are shown in Fig. 14. The overall diagram is shown in Fig. 15.

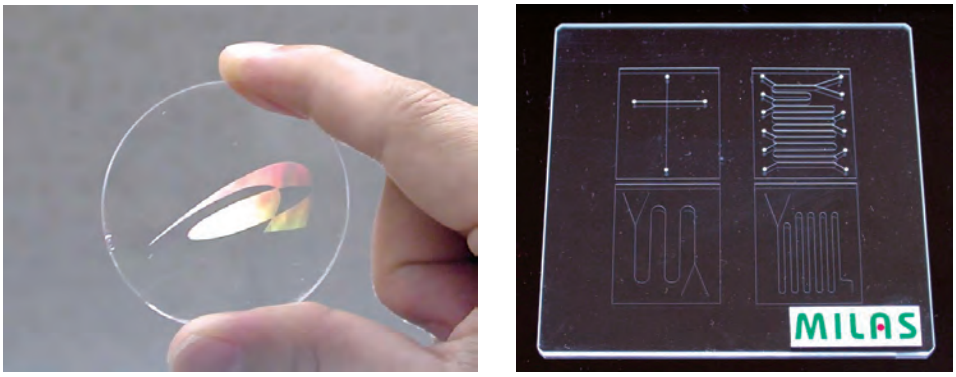


Fig. 12 Large surface area processing by LIBWE method onto silica glass: fabricated by laser scanning irradiation device (Colored area of the left figure is the scattering light from the transmission diffraction grating.)[14]

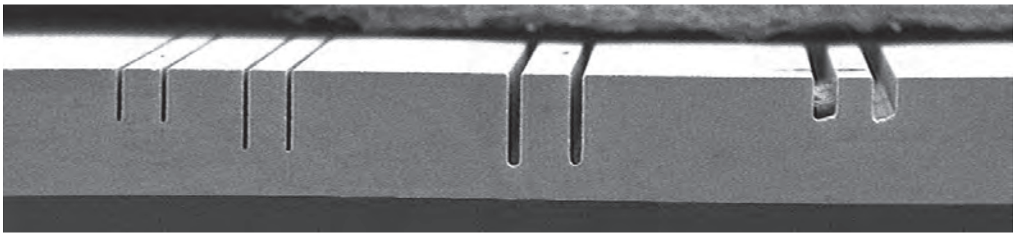


Fig. 13 Cross-sectional SEM photograph of deep groove processing by LIBWE method on aluminosilicate glass substrate (thickness of glass substrate: 0.5 mm). Groove width 20 µm (left), 50 µm (center), and 80 µm (right).

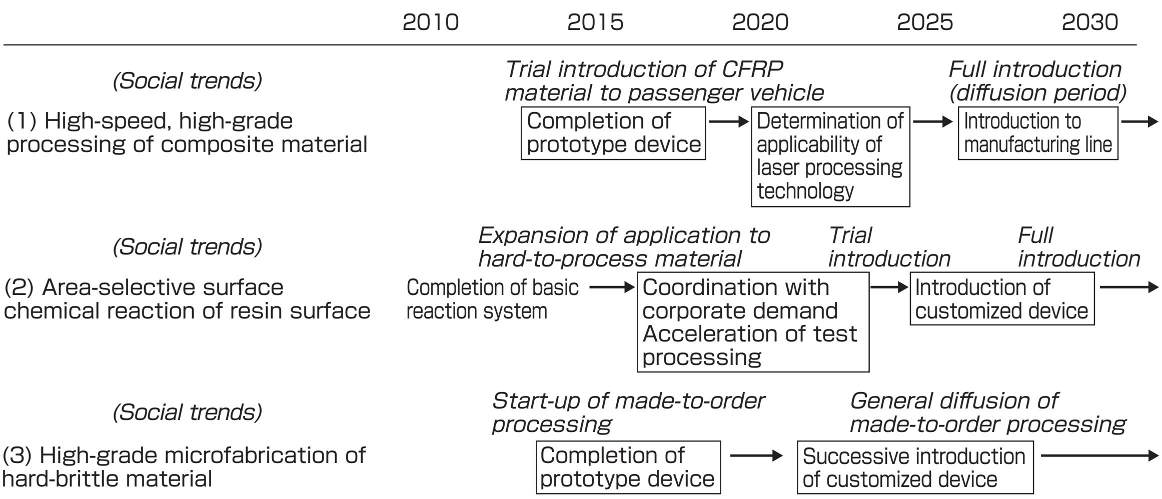


Fig. 14 Technology roadmap of specific case studies described in Chapter 3

Table 4. Social impact etc. of specific case studies described in Chapter 3

	Social impact	Expected new product group	Market size
Composite material processing	Improvement of fuel consumption by weight reduction of body	Ultra-lightweight passenger vehicle	25,000 tons (projection for international production of carbon fibers in 2020) 10 million cars (projection for international sales of eco-cars in 2020)
Surface chemical reaction	Expansion of application range of fluororesin	Surface modified fluororesin material for electrical and electronic application	10,000 tons (domestic sales of fluororesin in 2008)
Microfabrication of hard-brittle material	Shortened manufacturing lead time of customized micro-optical devices	Precision fabricated product using silica glass materials	2 trillion yen (domestic production of glass products in 2006) 73 billion yen (domestic production of silica glass in 2006)

To spread the results of laser application technology to society, first, prototypes of the processing device system are fabricated, and then, high-quality finished devices are shaped by repeated tests. The prototype devices have been completed for the CFRP process in Subchapter 3.1 and the glass microfabrication in Subchapter 3.3, and are currently in trial of whether they can perform and fulfill the on-site demands. The key point is close collaboration with the companies that may purchase the devices. Table 4 summarizes the social impact and others. The gaps between the future scenario and the current technological levels are as follows: (1) for composite material processing, it must be coordinated with the on-site production technology, (2) for surface chemical reaction, large surface area treatment technology must be established and the amount of chemicals used must be reduced, and (3) for microfabrication of hard-brittle materials, details of demand for custom items must be understood.

In general, in cases where laser processing technology is introduced, it is most appropriate for improving productivity in multi-variety variable quantity production. Current laser processing devices are successful in metal sheet processing (cutting and welding) and repair technology during manufacturing (yield is improved by conducting laser repair on defective products during manufacturing right in the manufacturing line; an example is correction of defects in LCD).

In material processing, maintenance of high-quality property and achievement of high-speed treatment often conflict, and by experience, it is known that the two are in tradeoff relationship, but in laser processing, both properties can be improved by carefully exercising process control. The specific examples presented in Chapter 3 are characterized by the addition of the viewpoint of material chemistry to surface treatment of hard-to-process materials. In the material processing where light is used, the processing target can be worked while maintaining balance of multiple factors. The Nobel Prize for Chemistry in 2014 was given to the development of the ultra-resolution fluorescent microscope.[15] By irradiating two lasers with different wavelengths (micro-spotlight and donuts pattern), the forced de-excitation phenomenon is induced in the fluorescent molecules, and the stimulated emission depletion (STED) allows microscopic observation at 10 nm scale that breaks past the diffraction barrier of 200 nm. Here, excellent results that surpass the conventional theory are presented when the roles of the two incident lights are clarified and are simultaneously irradiated. Currently, the microfabrication technology that uses this STED phenomenon is being studied at the fundamental research level.

Compared to other manufacturing technologies, the laser process may involve complex and expensive devices and systems, and this may lead to high costs. Therefore, in using lasers as part of production and analysis methods, the maintenance of economy that matches the market value is an important issue. Rather than using lasers for less expensive

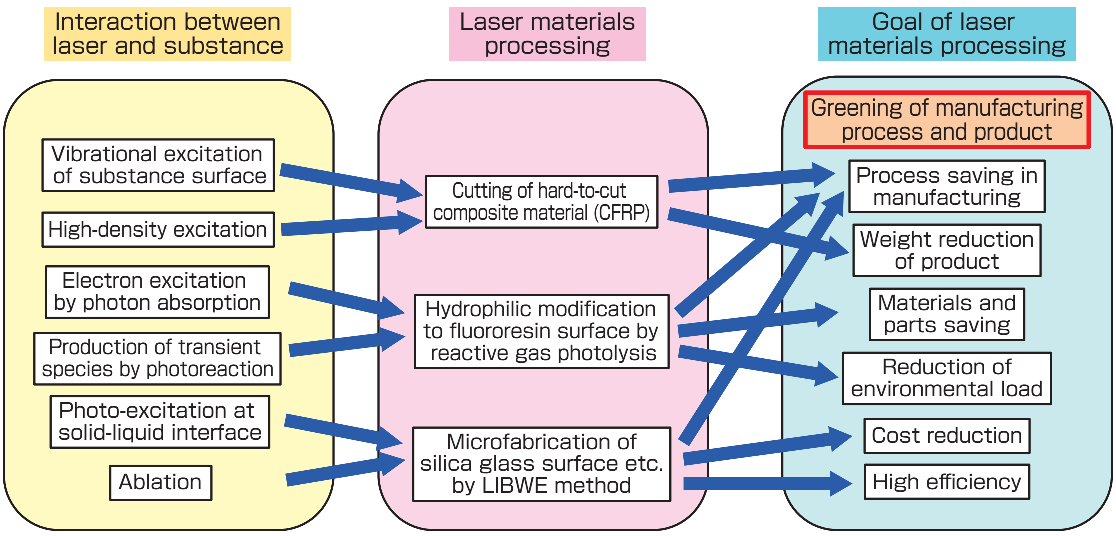


Fig. 15 Diagram of specific case studies described in Chapter 3

mass-production products, the main fields of application, in which the characteristic of laser treatment can be maximized, are substrate selective reaction by optimal wavelength and localized treatment to specific areas for which high added value is expected, or the processing control in ultra-short time from nano to femtoseconds. Since it can sufficiently handle 3D fabrication and digitized flexible production style, it is effective as a method to maintain traceability. As a future issue to fill in the gap with the scenario, further industry-academia collaborative efforts will be needed.

In this research, there are elements that depend on the performance of basic devices such as light sources and processing systems, and the results and performances demonstrated by the device used in trial has the potential of improving and accelerating the progress of the core device performance in the future. It is undeniable that the collaborative efforts for improving the device performance and advancing the process will be the main key for the future of processing technology. Therefore, the ability to widely grasp knowledge and to observe of the related technological fields, and serendipity are also important factors.

5 Summary and future issues

Through various applications of the material processing technology using high-power laser devices as described in this paper, more process saving and shorter time compared to conventional manufacturing processes will be achieved. Also, new elements, parts, and products can be supplied by realizing high-precision, high-quality microfabrication of hard-to-process materials, and the energy-saving property of the products may be improved further. In the progress of individual elements, attention is paid to the development of diffraction optical elements and spatial light modulators for irradiation optics. By actively utilizing the “duality of light” where light has both the properties of particles and waves, high-performance molecular beam and fine pattern making may be accomplished easily.

To promote further performance of the processing device system, breakthrough type innovation development is effective through the fusion of state-of-art Japanese technology with other areas (such as digitization of processing data, network transmission technology, or robotic technology). It is thought that the direction of innovation in manufacturing technology will be indicated through international competition.

Acknowledgement

The CFRP process is the result of research conducted under the New Energy and Industrial Technology Development Organization (NEDO) Project “Advanced Laser and Processing Technology for Next-generation Materials Project.” It was done jointly with the research institutions and companies that belong to the Advanced Laser and Process Technology Research Association (ALPROT). The high-quality microfabrication of hard-brittle materials by the LIBWE method is the result of research conducted with the members of the Laser Chemical Process Group (at the time), Research Institute for Innovation in Sustainable Chemistry, AIST.

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Discussions with Reviewers

1 Overall

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

This paper reveals the technology, along with its characteristic and usefulness, for high-precision, high-quality surface processing of substances and materials using lasers that the author has studied throughout the years. In the sense that it is a systematic description of the "laser processing technology," it is appropriate for *Synthesiology*. The technological content is of a high level. However, the first draft seemed merely a technological explanatory article, and not sufficient as a paper of "synthesiology." After you added the discussions based on our questions and comments, the paper has become more understandable.

Comment (Norimitsu Murayama, AIST)

This research is a synthesiological effort where new application of laser processing is sought by combining laser processing with other technologies. It is appropriate as a paper of *Synthesiology*.

2 Research objective and title of the paper

Comment (Naoto Kobayashi)

The title of the paper in the first draft is "Development of high-speed, high-quality laser processing technology." This gives an impression that the paper describes a general technological development. In *Synthesiology*, it is required that you state the objective of research to be realized in society, the scenario and the road taken to attain the objective, and the selection and integration of the elemental technologies. For the research objective, it is necessary to clarify (1) R&D for surface processing of materials to obtain a specific function, or (2) R&D for characteristic processing technology. Also, the title of the paper is recommended to be specific and appealing to the readers.

Answer (Hiroyuki Niino)

Thank you for your indication. I made revisions to discuss specifically and in depth the material processing technology using a high-power laser device in light of synthesiology. The first factor of synthesiology in this research is the background in which the development of innovative materials such as lightweight, high-strength materials and biocompatible materials progresses, and a new processing technology is demanded to go past the conventional method for integrating and realizing products. Specific corporate demands are increasing for high performance such as multiple function, micro-sizing, and high speed. By employing the material processing technology using light such as lasers, and by continuously promoting the advancement that is unique to this technology as shown by the temporal development from past to present, I clarified the research objective of this paper: "to promote the greening of the manufacturing processes and the products." Regarding the second factor of synthesiology, I described the scenario and the road taken to attain the goal by clarifying the specific research objectives through individual case studies. As for the third factor, I discussed the selection and integration of the elemental technologies. The developments by fusion and joining with technologies of other fields are also described where appropriate, in addition to the steady, solid, and ordinary development conducted in the manner of a linear model. The title was changed to "Green photonics for manufacturing and products by laser materials processing." Concerning "high-speed" and "high-quality," words originally included in the title, these qualities were explained in detail by adding specific property data to individual case studies.

3 Overall technological configuration

Comment (Naoto Kobayashi)

You had better state the research goal of what you wish to realize through high-speed, high-quality laser processing technology, the scenario to achieve the goal, and the integration of elemental technologies. Specifically, you can show the author's intention to the readers by showing an overview diagram of the technologies.

Comment (Norimitsu Murayama)

For the three case studies, please summarize in a diagram how you combined the laser technology with various kinds of technologies, and present them more clearly.

Answer (Hiroyuki Niino)

To clarify the overall concept, I described the three specific factors of synthesiology in this paper in Chapter 4, and added the overall diagram as Fig. 15, and provided discussions. Centering on the three case studies (hard-to-cut complex materials, reactive gas photolysis, and LIBWE method) shown in Chapter 3, "interaction of lasers and substances" (surface vibration excitation, high-density excitation, electron excitation by light, etc.) were presented as necessary factors, as well as the characteristics of laser processing that were featured in the case studies, particularly the greening of the manufacturing process and product.

4 New application

Comment (Norimitsu Murayama)

Please expand on the assumed scenario for the new applications of laser processing: (1) high-speed, high-quality processing of composite materials, (2) localized surface chemical reaction of the resin surface, and (3) high-quality microfabrication of hard-brittle materials. Please describe the social impact, new products, and the market size of these three new applications. Also, please include a time axis in the scenario. Add more detailed description about the gap between the scenario and current technologies, as well as the future issues to fill in the gap. I think it will be easier to understand if you illustrate the content with a figure.

Answer (Hiroyuki Niino)

In Chapter 4, I clarified the specific research objectives in individual case studies or the second factor of synthesiology, and described the scenario and the course for achieving the goal with the addition of a time axis. The gaps between the scenario and current technologies were listed, and the future issues to fill those gaps were described (Fig. 14). Specifically, the scenario assumed is as follows: (1) for high-speed, high-quality processing of composite materials, prototypes are expected to be completed around 2015, the applicability of laser processing devices will be determined after 2020, and it will be introduced to the manufacturing line between 2025 to 2030. Moreover, the social impact, expected new products, and market size were added (Table 4). For example, the social impact of complex material processing is expected to be “dramatic improvement of fuel consumption by weight reduction of the automobile body,” the expected product group is “ultra-lightweight passenger vehicles,” and the expected market size is 25,000 tons (projected international production of carbon fiber in 2020) and 10 million cars (projected international sales of eco-cars in 2020).

5 Issues for practical use

Question (Naoto Kobayashi)

As described in detail in this paper, there are many advantages in laser processing. Specifically, as seen in this paper, it is already partially used in the manufacturing process of flat-panel television and solar cells, but the diffusion seems slow. I think the cost is the greatest bottleneck. Including the CFRP processing and glass microfabrication as presented in this paper, which issues do you think must be overcome to achieve practical use (or commercialization)?

Answer (Hiroyuki Niino)

As issues toward practical use of the processing machine tool, price reduction, low electrical consumption, robustness, reliability, and others are important. From the perspective of those using the processing devices, the key is to be able to use it in the core system of highly flexible manufacturing that allows high degree of freedom for multi-variety appropriate-volume production. Therefore, it is desirable that the hardware of the processing device be customizable and the software and operation be freely changeable according to customer demand. The devices for sheet metal processing that is equipped with kilowatt level CO_2 gas lasers and fiber lasers belong in the macro-processing field dominated by a few worldwide companies, and products with performance that fulfill their demands are introduced whenever necessary. The world market for processing machine tools is one trillion yen per year, and the macro-processing field dominates about 60 %. On the other hand, in the micro-processing field, there are several hundred manufacturers around the world, and it is all out rivalry amongst the warlords. The individual case studies incorporate maximum utilization of laser properties, but the relatively small market scale is a major issue in maintaining and expanding the business. Like in the excimer laser exposure device in the LSI lithography process, if we succeed in improving the device performance steadily without delayed delivery in pace with the progress of exposure technology, we can gain the trust of the market for this product, even if it has the highest unit price among the laser devices.

6 Future trend

Question (Naoto Kobayashi)

In this paper, you mention the examples of IoT and Industry 4.0. Since the control by information and communication technology (ICT) can be done more easily for laser processing compared to other processing methods, fusion with ICT including remote processing will become extremely important in the future. Can you give us your opinion about the future trends of laser processing including incorporation of ICT, along with the situation of the current 3D printers?

Answer (Hiroyuki Niino)

As you indicated, machining tools equipped with lasers that can be remote controlled by ICT is being developed. The concepts described by IoT and Industry 4.0 are being studied in Japan, and some functions are already implemented in the actual machining systems. However, IoT and Industry 4.0 not only improve the performance of the machining system, but also are expected to build new business models that renew the relationship between the one who places the order and the one who receives the order. Also, since there will be global information unity of the manufacturing centers that are scattered around the world, it may provide global solutions to social and environmental issues.

For example, with the performance of the current 3D printers, days to weeks of work time are necessary to shape large objects of meter class dimensions. Therefore, it is impossible for a person to monitor the machines at all times. As the reliability and controllability of the devices improve and the performance can be sufficiently remote controlled, this technology has potential to affect the differentiation with competitors, geographical conditions of the factory location, as well as the organization of the company including work and employment style of the engineers.

7 International competition

Question (Norimitsu Murayama)

Your indication that Germany leads Japan in the R&D of laser processing technology arise from the background as follows: (1) Germany has continuously, without interruption, promoted this research as a major national project since the latter half of the 1980s, and (2) active employment of the laser processing technology (particularly for metal welding of automobile bodies) to actual manufacturing lines was done early in German automobile manufacturing companies. The lead by Germany in macro-processing field is significant. Also, major academic contributions by German scientists in the dawn of modern optics (19th century) set the starting point that continues today.

In Japan, with the foundation of the development of CO_2 gas laser equipment for manufacturing industry (project period; 1977~84) and the development of excimer laser equipment (1986~94), the sheet metal processing devices and the semiconductor lithography devices maintain worldwide share. However, we had a late start in the development of fiber laser equipment with kilowatt average power, and at this point, the presence of the Japanese fiber laser machine tools is not too high in the industrial trade shows for the latest laser processing devices.

The laser processing technology can be applied to a wide range of materials, and it is characterized by the fact that it can be applied to multitude of fields. Therefore, diverse R&D projects are promoted around the world, and Europe, North America, and Japan are the top runners in the world.

As the future development plan, the goal for light source development for industrial use should be the achievement of high power several tens to hundreds order higher than the current performance, and the following three are the candidate topics: (1) kilowatt level picosecond to femtosecond lasers, (2) fiber light-guided semiconductor lasers (high-power light-guided optical fiber in micron core diameter), and (3) deep ultraviolet range semiconductor lasers (gallium nitride system for ultra-small devices). The ranking corresponds to the degree of possibility of realization, and the core technology exists in Japan. Moreover, much high-level, basic academic research is being conducted in the optics field, and it is necessary to construct an organization that can quickly extract and develop the technologies that form the core of next-generation industrial application of such frontier research. I think the flexible setting of project scale, organization, and period according to individual topics, as well as scenario-driven collaboration among individual topics are effective. As explained in Subchapter 2.2, the laser processing device system is an accumulation of various high technologies, and at this point, the fusion with IT technology is promoted. The point is to lead the expansion of the market by discerning which and when a technological element should be developed heavily along the timeline. Therefore, it is important not to allow gaps in the joints of the multiple layers of technology and to increase affinity between the layers.

The majority of laser processing technology so far has been dominated by case studies utilizing the particle property of light. By employing the wave property of light, I think a new industrial application technology will develop in the future.

An IT system development framework utilizable without expert knowledge: MZ Platform

— Toward end user development in manufacturing industry —

Hiroyuki SAWADA*, Hitoshi TOKUNAGA, Yoshiyuki FURUKAWA

[Translation from *Synthesiology*, Vol.8, No.3, p.158-168 (2015)]

In recent years, manufacturing companies are being challenged to meet various social demands including short-term delivery, multiobjective production, quality assurance and traceability security. In order to meet these demands, keep and strengthen competitiveness, it is necessary for those companies to introduce IT. However, since it is often too expensive for small and medium sized enterprises to develop, operate and maintain IT systems, they cannot introduce them. We have developed an IT system development framework "MZ Platform" which enables manufacturing industry workers to construct and operate IT systems without professional IT knowledge, in order to encourage manufacturing companies to introduce IT systems. We describe our research and development approach and dissemination activities, and discuss effects of MZ Platform.

Keywords : Component-based development, software component, manufacturing industry, IT system, end-user development

1 Introduction

Recently, manufacturing industrial environment is becoming more and more competitive. Manufacturing companies are being challenged to meet increasing demands including short-term delivery, multiobjective production, quality assurance and traceability security. It is widely recognized that systemization of workflow and digitization of documents by introducing information technology (IT) is effective in meeting those demands, and many kinds of software applications are currently available for engineering design and manufacturing such as CAD systems. However, especially for small and medium sized enterprises (SMEs), the development, operation and maintenance costs of IT systems are too high, and it is difficult to assign a worker with sufficient knowledge and experience of managing IT systems. As a result, it is often the case that a manufacturing company fails to introduce and make use of IT systems.

This research aims to encourage manufacturing companies to introduce IT systems. In order to achieve this aim, we have developed and diffused an IT system development framework for end user development,[1] called "MZ Platform," which enables manufacturing industry workers to construct and operate IT systems without professional IT knowledge. That is, this research involves two kinds of activities: one is technological development of an IT system development tool for non-professional programmers, the other is diffusion of it with establishment of an end user support organization.

2 Technological development

2.1 Target of technological development

"MZ Platform" is a component-based IT system development tool which enables a worker to build up an IT system without writing source code. Conventionally, in order to build up an IT system, it is necessary for a worker to learn a programming language and write source code by using it. However, it is quite difficult for a worker without sufficient IT knowledge to do so. Therefore, we have employed a component-based development method[2] in order to remove those difficulties.

A component-based development method is a way of building up a whole IT system by combining small separated off-the-shelf programs named software components. This is well known as an extension of object oriented development in the field of software engineering. Commercial component-based development tools, such as Microsoft Visual Studio,[3] are currently available.

However, though these tools provide a function of making up a basic structure of a whole IT system by combining components, the programmer has to write source code for detailed functions of each component. That is, these conventional tools are for users with considerable knowledge and experience of programming, and are too difficult for a user with insufficient IT knowledge to use. Therefore, we have established our research objective of developing a full component-based IT system development tool which

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completely eliminates source code writing.

2.2 Technological issues and development approach

This technological development has two major issues as below.

(1) Proof of usefulness of full component-based development

It is necessary to prove that it is possible and useful to build up an IT system for practical use in production lines of a manufacturing company, in accordance with the manner of full component-based development which eliminates source code writing for detailed functions of software. Since theoretical proof is impossible, we illustrate the usefulness by case studies.

(2) Preparation of a set of components

It is necessary to prepare a set of components with sufficient variety and generality which improves efficiency of development of an IT system satisfying various requirements of manufacturing companies. It is most important to decide classes and functional granularities of components.

In order to work on these issues, we conducted our research work through development of practical IT systems for manufacturing companies (Fig. 1). We collaborated with several manufacturing SMEs to build up practical IT systems, such as a production management system, for each of them, and then illustrated the usefulness of our full-component based development method by these case studies. In addition, we studied what kinds of components are necessary through the case studies and decided classes and functional granularities of components.

We conducted our research work in accordance with the following steps.

(i) Hearing to each manufacturing company
(ii) Workflow analysis and establishment of requirements of the IT system for the company
(iii) Making up components necessary for the IT system
(iv) Development of the IT system
(v) Evaluating the IT system and extracting standard functions
(vi) Reorganizing the equivalent functions of the IT system by combining the standard functions
(vii) Making up components based on the classes of the standard functions

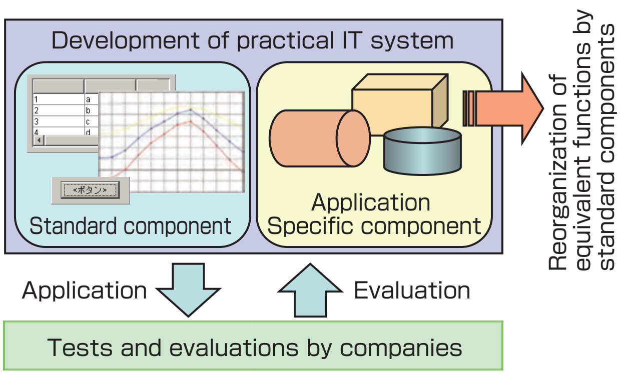

Fig. 1 Research work through development of practical IT systems

Within the above steps, steps (i) to (iv) are research activities associated to "Proof of usefulness of full component-based development," and (v) to (vii) are those associated with "Preparation of a set of components." We refer to "a component based on the classes of the standard functions" as "a standard component" in the following part of this paper.

2.2.1 Development of practical IT systems for manufacturing SMEs

We have developed practical IT systems for manufacturing SMEs, including a process management system to monitor progress of processes and a technical knowledge management system to search and show necessary technical data. We have conducted the development in order to illustrate the usefulness of full component-based development, and to investigate the essential and general problems faced by manufacturing SMEs. Before developing the IT system, we conducted a hearing to the manufacturing company to decide its specification. Some of company workers' opinions and requirements were not necessary or appropriate to reduce load of workers. For example, too much data input work might be necessary to operate the IT system they required. However, we accepted their opinions and requirements as much as possible, because we thought it was necessary and important to understand their issues and problems accurately.

We developed each IT system according to the following steps.

(i) Identifying necessary functions
(ii) Breaking down each function into sub-functions recursively until we obtained elemental functions which cannot be decomposed properly
(iii) Making up components for each elemental function
(iv) Building up an IT system by combining those components

During the development, we kept in close contact with the companies, and repeated tests, evaluations and improvement of IT systems every few months.

Through the experience of developing IT systems for practical use in the full component-based method, we found that this method is useful for improving IT systems. An IT system built up by the full component-based method consists of sub-functions highly independent of each other. Therefore, when it is demanded to improve the IT system, since it is easy to focus on and identify what should be modified, it is possible to reduce work load for the improvement. This is quite suitable for developing companies' work management systems which have to be adapted to changes of business forms. This also means that classification of component functions is very important for making the best use of the full component-based development method.

We found two major essential issues for manufacturing SMEs, through these IT system development case studies.

One is an issue of workflow analysis to find out problems in each company and work out solutions. When a worker conducts workflow analysis, he/she usually claims problems and requirements from his/her own viewpoint. It is often the case that some requirements are in conflict with others. For example, a manager often requires production data and results of data analysis in detail. However, in order to obtain detailed information, workers have to input a lot of data. It comes into conflict with workers' requirement of reducing work load. In order to improve working process by introducing IT, it is important to estimate costs of introducing and operating an IT system, and effectiveness of the IT system in improving the working process, and to make the aim and the objective of introducing the IT system clear, and then to establish a consensus among all the stakeholders including managers, workers and IT system developers. We show several examples of companies in Chapter 4. They have succeeded in introducing IT systems mainly because they made their targets clear.

The other is an issue of information management in an integrated manner. We have developed various IT systems such as a process management system and a technical information management system. Essentially, they are used to manage a lot of data separately recorded on paper or electrical documents in an integrated manner, to resolve inconsistency among those data, and to reduce work load.

The above knowledge obtained from the experiences were very useful for deciding classes of the standard components and to guide companies in their introducing IT systems.

2.2.2 Preparation of standard components

As described in the previous section, we have developed the IT systems in order to understand the essential problems faced by manufacturing SMEs and to find out necessary functions for improving their work by introducing IT systems. Therefore, components used for the development were made based on the necessary functions for each company, and some of them were not applicable to other companies. We reinvestigated the means of executing necessary functions and reorganized functions equivalent to the developed IT systems by combining the standard and highly generic functions, and then we made up a set of standard components with sufficient variety and generality which improves efficiency of development of an IT system satisfying various requirements of manufacturing companies.

We conducted the above work by dividing and generalizing the component functions for specific companies. Those components have elemental functions which cannot be divided anymore as processes in each company's workflow. However, those elemental functions can be still divided in terms of software program processes. We divided those elemental functions and decided on standard functions applicable to the development of IT systems for various companies.

On the other hand, we developed a new component with generic functions for similar functions used in various IT systems. For example, many companies record their various data in the form of tables. Since the data table structures such as data items and properties are different in each company, it is impossible to use one company's data table in another company. This means that it is impossible to use one specific data table component for another company. However, if the data table component has a function to change its data table structure, it can be used for various IT systems.

Fig. 2 shows an example of the preparation of standard

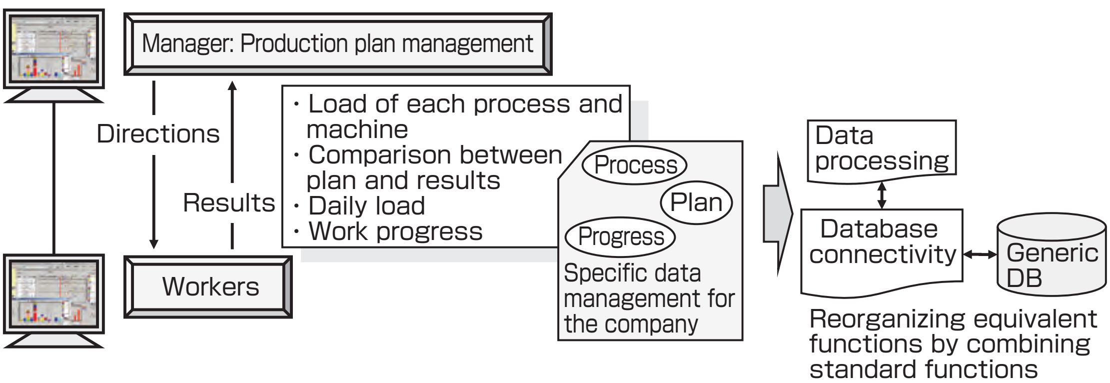

Fig. 2 Example of preparation of standard components in a process management system

components for a data management function of a process management system developed for one manufacturing company. This company did not have an IT system and managed their manufacturing data in the form of paper documents. Therefore, the manager could not follow manufacturing process progresses in real time. This process management system was developed to solve this kind of problem. In this development, we made a specific component which stored and aggregated data necessary for management. We reinvestigated the component function and divided the component into two separate components with data storing functions and data aggregating functions. Furthermore, we decided to use generic database software to store data, developed a new standard component to connect with databases, and used it for data storing. As for data aggregating functions, we developed a standard component with generic data processing functions including statistical and table calculations and replaced the company specific component with the standard one.

As shown in this example, MZ Platform does not always provide all the necessary functions for itself. We regard it as important to connect MZ Platform with other software systems and utilize their useful functions. It is also useful in interacting with existing systems such as an accounting system thereby building up a total information management system in a company.

Finally, we prepared about 180 kinds of standard components which collectively provided most of the necessary functions of IT systems for manufacturing SMEs. After that, we added new components continually in response to users' requests including demand for Web functions. Currently, MZ Platform has more than 200 kinds of standard components.

2.3 Architecture and functions of MZ Platform

MZ Platform consists of the application builder which provides functions for development and execution of an IT system, the application loader which executes a developed IT system, and standard components for IT system development. All of them are implemented in Java language.[4]

2.3.1 Application builder

The application builder provides a user interface for IT system development and test run. In comparison with conventional source code writing, a user builds up an IT system easily by combining components on the application builder's graphic user interface (GUI). Fig. 3 shows the process of IT system development on the application builder.

A user selects necessary components from a popup menu and describes execution processes in the form of a chart expressing connections between components. Display layout of GUI components is arranged on another display layout window. The user can easily add and modify a function of the IT system by adding, removing, connecting and disconnecting components.

Ease of modification of IT system functions is one of the advantages of MZ Platform for adapting an IT system to continual work improvement. Conventionally, it is difficult to modify a once developed IT system, and its modification is very expensive. Therefore, it is often difficult to conduct work improvement which requires IT system modification. That is, it is often the case that the workflow is fixed by introducing an IT system and that it becomes impossible to improve work anymore. MZ Platform avoids this kind of problem and enables continual work improvement.

2.3.2 Application loader

The application loader is a tool for executing a developed IT system. Fig. 4 shows the relationship between the application builder and the application loader.

2.3.3 Standard components

MZ Platform has currently more than 200 standard components for IT system development of manufacturing companies. Table 1 shows an outline of MZ Platform

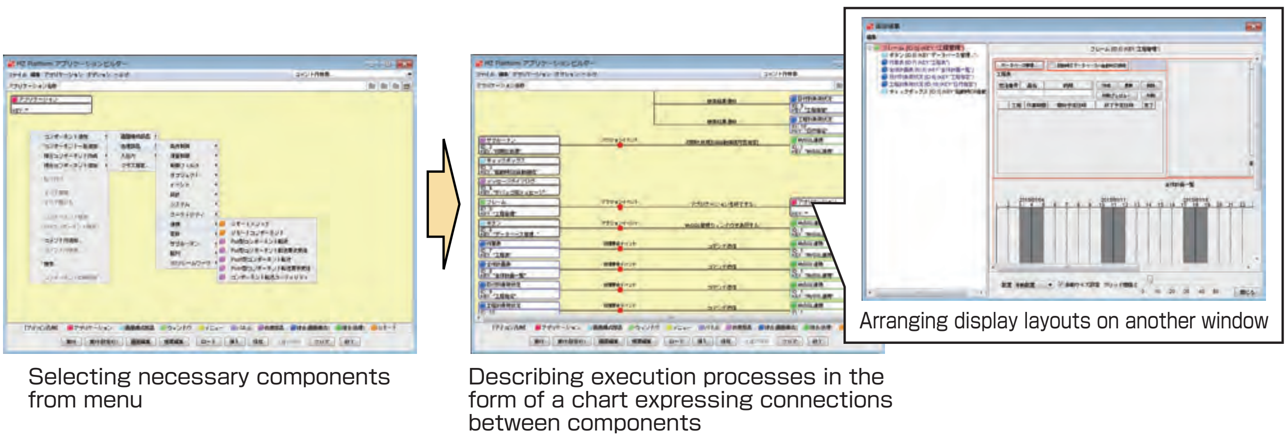

Fig. 3 IT system development on the application builder

Table 1. MZ Platform standard components

Classification		Explanation	Components
GUI	Operation	For user operations from GUI such as button click, text input and data display	Frame, Dialog, Button, Text field, Label, Image viewer, Menu bar, Tool bar, Table, Tree etc.
	Chart	For displaying table data in the form of various graphs	Bar chart, Line chart, Area chart, Plot chart, Pie chart, Gantt chart, Pareto chart etc.
Process		For data processing	Calculation, Logical operation, Table data processing, Function, Subroutine, External program interface etc.
IO		For printing and data input/output with external data sources including files and databases	Paper, Database access, Excel file access, CSV file reader/writer, Image file reader/writer, Serial port connector etc.

standard components.

In addition to the standard components, a user can create his/her own component by Java programming and use it for his/her own IT system. MZ Platform also provides documents, template files and sample application files for a user with programming knowledge to make a new component.

2.3.4 Evaluation of MZ Platform

We conducted evaluation of MZ Platform from 2004 to 2005 in order to quantitatively estimate the effectiveness of MZ Platform in reducing work load of IT system development. We evaluated MZ Platform from two viewpoints: one is the ease to learn how to use MZ Platform, the other is the time reduction of programming.

(1) Ease to learn how to use MZ Platform

We evaluated the ease to learn by comparing the learning time period with other programming language. We asked several professional programmers to learn how to use MZ Platform. Then, we compared the learning time period with how long they had taken to learn a conventional programming language.

We obtained the result that they were able to learn MZ Platform in no greater than half of the time for learning MFC/C++[5] or Java.

(2) Time reduction of programming by using MZ Platform

We developed IT systems for practical use for several manufacturing SMEs by using MZ Platform. Then, for each developed IT system, we asked a professional programmer to estimate how long it took to develop an equivalent IT system by using a conventional programming language. Table 2 shows the results of comparison of IT system development work load of MZ Platform with a conventional programming language.

In some of above cases, the worker who made the IT system by using MZ Platform is different from the professional programmer who estimated the working time by using a conventional language. Additionally, since the working time was estimated roughly, the comparison is not accurate numerically. However, it is enough to show the effectiveness of MZ Platform in reducing time of programming.

3 Diffusion of MZ Platform

In order to achieve our research aim of “end user development for manufacturing SMEs,” in addition to the development of MZ Platform, it is necessary to disseminate how to develop and introduce IT systems, to educate workers in utilizing MZ Platform, and to establish an end user support organization for SMEs. Therefore, we worked on diffusion of MZ Platform as below.

(1) Dissemination seminars

We have held dissemination seminars at AIST regional bases,

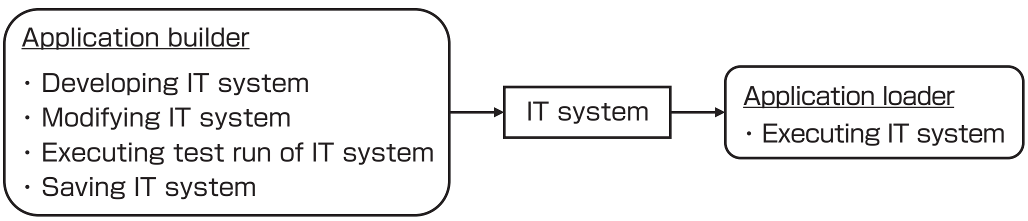

Fig. 4 Relationship between the application builder and the application loader

Table 2. Comparison of IT system development work load

Company	IT system	Working time	Comparison with a conventional programming language
Company union (Nagano)	Process management between companies	30 man-days	Less than 1/4
Cutting (Osaka)	Technical information management	3 man-days	Less than 1/10
	Quality check	10 man-days	Less than 1/3
Sheet metal working (Nagano)	Process design support	7 man-days	Less than 1/4
Press working (Nagano)	Production and document management	30 man-days	Less than 1/10
Injection molding (Oita)	Production plan and result management	45 man-days	Less than 1/3
Metal mold (Tokyo)	Progress management	30 man-days	Less than 1/4
Grinding (Fukuoka)	Order, process and quality management	25 man-days	Less than 1/3

prefectural research institutes and industrial associations all over Japan including 44 prefectures. At the seminars, we introduced functions of MZ Platform and case studies at manufacturing SMEs.

(2) MZ Platform consortium

We established "MZ Platform Consortium" as one of AIST consortia in 2004. We delivered MZ Platform to the members, held training courses and answered technical questions from the members via electrical mail. There were corporative and individual memberships. Membership fees were 1000 yen a year.

MZ Platform consortium closed at the end of June, 2014. Currently, MZ Platform is delivered to registered users by free download. We had 456 registered corporative and individual users in total at the end of December, 2014.

(3) Establishment of an end user support organization

We have established an end user support organization consisting of prefectural research institutes for regional consultation about IT system development. In addition, in accordance with the AIST technical training program, we accept company workers and educate them to build up their own IT systems. Furthermore, since it is necessary to make use of MZ Platform in business for lasting diffusion and user support, we work on making commercial license contracts of MZ Platform with software vendors.

Fig. 5 shows an overview of the MZ Platform support organization. A prefectural research institute primarily gives advice to manufacturing SMEs. A software vendor onerously gives information equipment and services such as designing databases. An AIST regional research base manages those activities. The Advanced Manufacturing Research Institute educates and trains persons in charge.

We do not always develop and introduce an IT system in accordance with the support organization shown in Fig. 5. In some cases, no software vendor joins since the SME decides to develop its IT system for itself.

When a software vendor does not have knowledge about MZ Platform, we usually propose that it joins a case study to

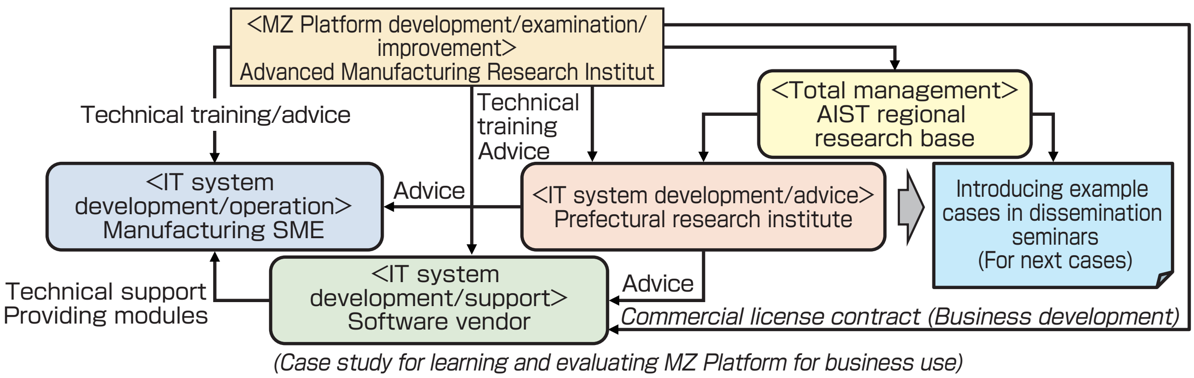

Fig. 5 MZ Platform support organization

evaluate whether MZ Platform is promising for its business. When it decides to use MZ Platform for its business, we arrange that it makes a commercial license contract with AIST to develop MZ Platform business.

4 Case studies

We introduce 3 case studies of IT system development in manufacturing SMEs using MZ Platform.

4.1 Production plan and result management system of an injection molding company (Oita)

Ohkawa Mould Designs & Engineering, an injection molding company in Oita Prefecture, has developed a production plan and result management system with the support of the Oita Industrial Research Institute. In this company, production plans and results were written conventionally on paper or white boards by hand. Therefore, states of production were checked every half-day at most and troubles due to miswriting were inevitable. The company developed an IT system to digitize information about production plans and results, thereby managed delivery precisely by checking production states every one hour, and reduced working time by 20 % on average. The company got a special award for IT management from the Kyushu Bureau of Economy, Trade and Industry for this IT system development in 2007. Furthermore, the success of this IT system development led to the pilot project of IT system development for SMEs[6] conducted by Oita Prefecture from fiscal year 2008 to 2010.

Fig. 6 shows an overview of the production plan and result management system. It uses conventional excel files to make and view production plans. Based on the production plans, working plans are made and working directions are issued. Production results are entered via handy terminals with barcodes, and then all the information is automatically stored in a database.

This IT system development process consists of 4 stages as written below. Time period for each stage is written in parentheses.

(1) Preparation stage (one month)
- Organization of a IT system development team
- Determination of the target of digitization
- Assignment of work to each member of the IT system development team

(2) First stage (three months)
- Analysis of the workflow
- Design of a new workflow with the IT system
- Design of the IT system

(3) Second stage (two months)
- Programming (making the MZ Platform application)
- Hardware selection

(4) Third stage (two months)
- Trial and revision

It was very important to clarify the target and objective of the IT system development, and to make responsibility of each member clear at the preparation stage. Furthermore, the Oita Industrial Research Institute played an important role in the management as well as construction of the IT system.

Company workers sometimes avoid to say their opinions frankly to their seniors or bosses. This might often cause failures in sharing problems and, as a result, in developing the IT system. The researcher of the Oita Industrial Research Institute gave impartial opinions, enabling workers to discuss frankly, and thus avoided such kind of failures.

4.2 Order, production and stock management system of a surface modification company (Nagasaki)

Shinto Industrial, a surface modification company in Nagasaki Prefecture, has developed an order, production and stock management system with the support of a software

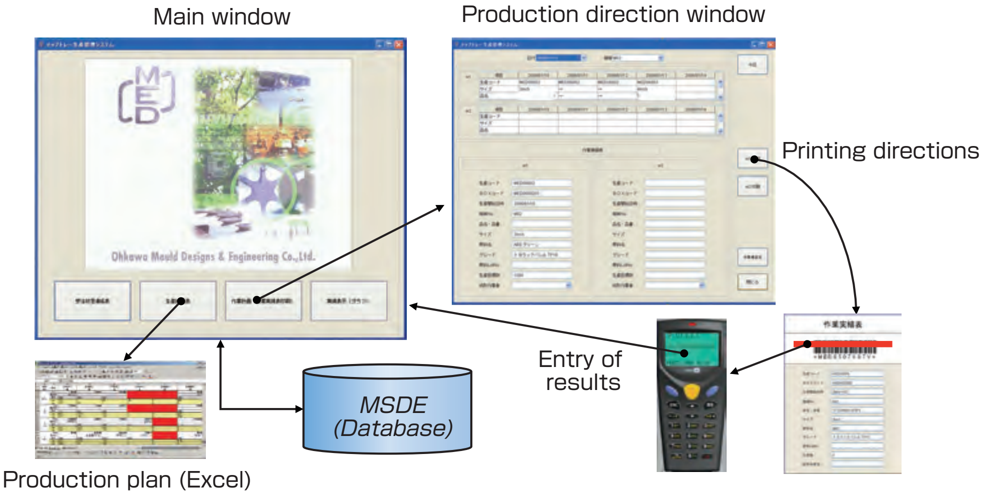

Fig. 6 The production plan and result management system (provided by Oita Industrial Research Institute)

Table 3. Tasks about the order, production and stock management system development

(1)	Creating the workflow and listing paper documents	Shinto Industrial
(2)	Determining the target of digitization	Cooperation
(3)	Design of the database	Cooperation
(4)	Design of the graphic user interface	Cooperation
(5)	Programming (making the MZ Platform application)	Software vendor
(6)	Test run	Cooperation
(7)	Operation of the developed system and further development	Shinto Industrial

vendor. This company had planned to digitize paper documents, estimate costs correctly by managing all the information in an integrated manner, and improve production efficiency. However, the plan was suspended because a suitable IT system development tool was not available. The company found MZ Platform and began to develop an IT system by using it. Fig. 7 shows the architecture of the IT system.

This IT system enabled the company to obtain the data about production and working ratio of equipment and analyze those data for improving efficiency. In 2009, for this IT system development, the company got a special award for IT management from the Kyushu Bureau of Economy, Trade and Industry and was certified as a practical IT management company by the Ministry of Economy, Trade and Industry.

In this case study, it was very important that the company and the software vendor shared work appropriately. Table 3 shows tasks involved in the order, production and stock management system development. They clearly divided the tasks into what the company had to do by itself and what should be done with professional IT knowledge of the software vendor, and then carried out the tasks efficiently. In the end, the company became able to operate, manage, and maintain the developed IT system for itself.

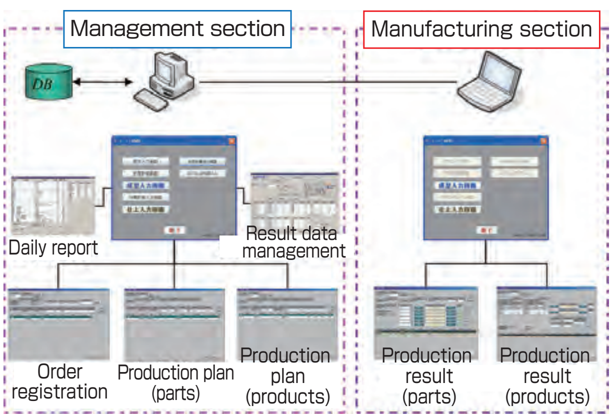

Fig. 7 The order, production and stock management system (provided by Shinto Industrial)

4.3 Order and progress management system of a metal mold company (Saga)

Shotoku Zerotec, a metal mold company in Saga Prefecture, has developed an order and progress management system with the support of the Industrial Technology Center of Saga and a software vendor. Though this company had introduced a package software system, it was hard to input daily working data correctly. Therefore, in order to input daily working data easily and correctly, the company developed an IT system with a real time record input function using barcodes. Figure 8 shows its overview.

Barcodes are printed on all the workers' name plates, machine tools and working directions. A worker can input all the data only by reading the barcodes by a barcode reader, and the input time is automatically recorded. By this IT system development, the company got a special award for IT management from the Kyushu Bureau of Economy, Trade and Industry in 2008, and was certified as a practical IT management company by the Ministry of Economy, Trade and Industry in 2010.

It is notable, in this case study, that the company utilizes the collected data for improving manufacturing processes by calculating the cost of each process correctly. Fig. 9 shows an example of the improvement of a manufacturing process.

The company calculated the cost of each manufacturing process for one product and found that the cost of only one process exceeded the price of the product. Then, the

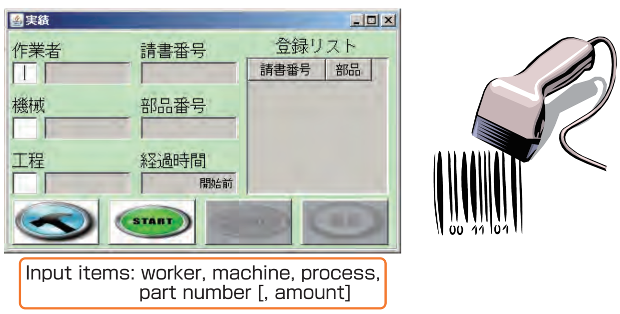

Fig. 8 The real time record input function using bar codes (provided by Shotoku Zerotec)

company improved the manufacturing process and succeeded in making a profit. It is important that the company made workers recognize the problem. The workers already knew that moment stops occurred. However, they did not associate that to the cost of the manufacturing process. The workers became aware of the costs as numerical data, recognized the problem, and then solved it.

4.4 Effectiveness of end user development and MZ Platform

As shown in the above case studies, those companies made the target and objective of IT system development clear at the early stages of development, and it led to their success. They were able to make the target and objective clear, because they worked on programming for themselves with the support of the prefectural research institute researchers and the software vendor programmers.

Manufacturing companies often fail to develop IT systems, especially in the case of outside order, because the manufacturing companies cannot communicate with the computer programmers very well. There exists difficulties in communication between a manufacturing company without IT knowledge and a computer programmer without manufacturing knowledge. If a manufacturing company worker becomes able to do programming, even though he/she does not have professional IT knowledge, he/she learns a way or manner of developing an IT system and becomes able to think about its target and how to make it. This kind of experience of programming and knowledge are useful for collaborating with computer programmers as well as for the company's own system development. This is typically shown in the case study of Shinto Industrial described in Subchapter 4.2.

When end user development is mentioned, merit of the user's own development is often described. However, we claim that it is much more effectiveness when collaboration between end users and professionals is encouraged through end users working on programming. The case studies described in this chapter illustrate that MZ Platform is an effective tool for promoting end user development.

5 Conclusion

"We had no way to realize our ideas for improving our working efficiency. However, we now have MZ Platform. We think about reducing our work load and improving our work every day, and realize our ideas as an IT system by using it."

This is a comment from a user in a manufacturing company. At the beginning of our research, we intended only technological contribution to reduce work load about programming. Bringing out individual workers ability for improving their work by providing an easy-to-use tool to realize their ideas goes far beyond our intentions. We consider it as the greatest effect of MZ Platform.

In this research, we worked on diffusion of MZ Platform very much, as a result of reviewing our activities at early stages of research. When we released the trial edition of MZ Platform, we developed IT systems using it with some manufacturing companies. Though the IT systems had sufficient functions for practical use, the companies did not use them. We conducted hearings to the companies and found that they had difficulties in assigning workers to operate, utilize, manage and maintain the IT systems. Then, we began to work hard on education of workers and establishment of a user support organization.

Diffusion is not only to deliver research results. It is important to think about the final use cases from the viewpoint of intended users and to plan a strategy for reaching the goal. We have learned this from this research, which has been instructive and useful for our future research.

We recognize MZ Platform to be almost completed as an IT system development tool. We will improve MZ Platform

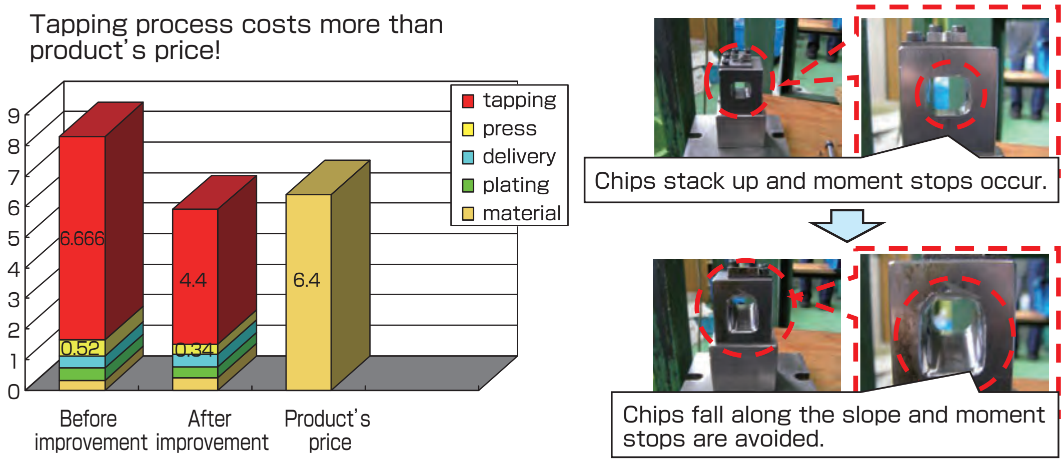

Fig. 9 Improvement of manufacturing process by utilizing the collected data (provided by Shotoku Zerotec)

continually by introducing available new technologies. Technology in the field of IT is progressing rapidly, and it is often the case that a technology not recognized five years before has become commonly used. MZ Platform has a mechanism to improve its functions by introducing a new technology as a new component. We are going to utilize MZ Platform not only for IT system development in manufacturing companies but also as a platform for our future research work by introducing new technologies . In addition, we will use MZ Platform to implement our research results as software applications and introduce them into companies.

Acknowledgement

This research has been conducted in the framework of the projects of "Research and development for integration of manufacturing and information technology" and "Support for succession of basic skills in manufacturing small and medium sized enterprises" by the New Energy and Industrial Technology Development Organization (NEDO). We would like to thank the Oita Industrial Research Institute, Ohkawa Mould Designs & Engineering, Shinto Industrial and Shotoku Zerotec for providing us their materials.

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Discussions with Reviewers

1 Overall summary (Motoyuki Akamatsu, AIST)

This paper describes the development of a tool which enables users to make software applications without professional IT knowledge, in order to solve a problem of manufacturing SMEs having difficulties in developing and introducing IT systems due to heavy work load. Since it is difficult to make a software application by writing source codes, the authors developed a tool to build up an IT system by combining components without any source code writing. It is necessary to prepare a set of standard components in order to realize full component-based development. The authors used a strategy to make the standard components through development of IT systems for practical use with manufacturing companies. It is most important to diffuse the tool. The authors diffused it by organizing a support network consisting of manufacturing companies, software vendors, AIST and prefectural research institutes.

2 Standardization of components

Question (Motoyuki Akamatsu)

The authors claim that it is necessary to standardize components in order to realize full component-based development. What does "standardization" mean in this paper? What kind of components can be regarded as standard? In addition, please explain how to make standard components.

Comment (Naoki Ichikawa, AIST)

It would be better to explain the developing process of the standardized components. Was there an initially established plan for the components under some assumption or was there a trial and error process to decide the components in accordance with practical specifications?

Answer (Hiroyuki Sawada)

“Standardization of components” means “preparation of a set of components with sufficient variety and generality which improves efficiency of development of an IT system satisfying various requirements of manufacturing companies.” Each component belonging to the component set mentioned above is a standard component, which means a component based on the classes of standard functions. We added an explanation that we refer to “a component based on the classes of the standard functions” as “a standard component.”

We made standard components by dividing and generalizing component functions for specific companies. We divided the component functions for specific companies and decided on standard functions applicable to the development of IT systems for various companies. On the other hand, we developed a new component with generic functions for similar functions used in IT systems of various companies. We added the above explanation in Section 2.2.2 “Preparation of standard components.”

We firstly established our objective as preparing a set of components with sufficient variety and generality which improves efficiency of development of an IT system satisfying various requirements of manufacturing companies, and planned to make it possible to build up various IT systems by combining highly generic standard components. We made specific components to extract necessary functions for IT system development and to gain knowledge for preparing a set of standard components.

3 Demands on companies in IT system development

Comment (Naoki Ichikawa)

It might be necessary to mention an attitude which a company should have when introducing and developing an IT system. It would be better to clearly explain that a company would fail if it only expects something good as shown in the case studies. I recommend the authors to explain what a company should take into account; that is, to make the necessity, objective and effect of introducing an IT system clear before introducing an IT system.

Answer (Hiroyuki Sawada)

At the beginning of the paragraph that starts with “One is an issue of …” in Section 2.2.1 “Development of practical IT systems for manufacturing SMEs,” we mentioned an issue of workflow analysis and described the importance of making the aim and objective of introducing an IT system clear.

4 Introduction of MZ Platform to companies

Comment (Naoki Ichikawa)

Though the authors write in a matter of fact manner, I think that they examined various alternatives during the development of MZ Platform. It would be better to explain at what stage of development they decided to introduce MZ Platform to companies, and important turning points at which they changed functions or specifications of MZ Platform by reflecting feedback from the companies.

Answer (Hiroyuki Sawada)

In the first part of Section 2.2.1 “Development of practical IT systems for manufacturing SMEs,” we explained what we regarded as important in hearings to companies and the repeated process of evaluation and improvement during the IT system development. Furthermore, as the knowledge obtained from the process, we explained that classification of component functions is very important in making the best use of the advantage of the full component-based development method which improves IT systems easily.

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.

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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).

Inquiries:

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Letter from the editor

In this issue, we present three papers on the "thermal converter for AC voltage standard," "green photonics for laser manufacturing," and "IT system development tool for the manufacturing industry." As the contents of the papers are diverse, it is natural that scenarios for R&D and use in society as well as the realization process differ according to the research field and the nature of technology. Therefore, I believe the significance and mission of this journal are to continuously publish and accumulate papers that describe the specific case studies of utilizing the results of various R&D in society for diverse technological fields.

While the contribution of science and technology in society spans over a wide range of fields, there was recent news about global environmental protection. A major automobile manufacturer announced that its newly constructed factory would aim to decrease its CO_2 emission by half. This would probably involve employment of advanced technology and large cost burden. However, I think it is one of the significant efforts to avoid global warming and to realize a sustainable society. For the involvement of science and technology in achieving a sustainable society, as exemplified by the debate about spreading the use of renewable energy versus increased cost burden on society, it will become increasingly important in the future to engage in multifaceted discussions and evaluations pertaining to the social value of technology and cost burden. I hope the papers in this issue will become a reference of useful knowledge to support such discussions.

(Masakazu YAMAZAKI, 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

"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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