"SumiTune" High-Precision Temperature Distribution Control System for Single-Wafer Film Deposition Equipment

Shigenobu SAKITA*, Koichi KIMURA, Katsuhiro ITAKURA, and Akira MIKUMO

We supply heaters for heating semiconductor wafers in the single-wafer film deposition processes. Semiconductor wafers are indispensable for 5th generation communications, artificial intelligence, automatic driving, and large-capacity data storage in data centers. The refinement of semiconductor circuits requires the formation of uniform films on wafers, and this demands uniform temperature distribution in the wafers. Conventionally, heaters have been divided and arranged in concentric zones, but this does not cover the subtle unevenness of circumferential temperature distribution caused by various factors in the device environment. To overcome this challenge, we have developed a multi-zone heater and a controller capable of high-accuracy control.

Keywords: SumiTune, multi-zone control, semiconductor, single-wafer film deposition equipment

1. Introduction

Semiconductor products are indispensable for 5th Generation (5G) communication (next-generation standard), automated driving technology enabled by artificial intelligence (AI), and large capacity storage for data centers. A variety of heaters are used in the semiconductor manufacturing process to heat semiconductor wafers. Notably, wafers must be heated in many steps in the front-end process, including the application of a photoresist film on wafers, chemical vapor deposition (CVD) to deposit various types of films on wafers, and dry/wet etching to etch the wafer surface. It supports different temperature ranges (room temperature to 1,000°C), using various heaters.

Recently, there has been a growing need to increase the processing speed of multi-core central processing units (CPUs) and GPUs*[1] for AI and to increase the storage capacity of data centers. Against this backdrop, there has been growing demand for miniaturization of the circuit wiring to increase the integration degree of processing units. This requires formation of a homogeneous film. It is also essential to achieve uniform temperature distribution on the wafer surface.

SumiTune, which is introduced in this paper, achieves highly uniform temperature distribution on the wafer surface by means of multi-zone control, which was difficult to achieve in the conventional single-wafer film deposition equipment. This is a next-generation system that can meet the demand for miniaturization of the circuit wiring.

2. Semiconductor Deposition Equipment

There are two main types of semiconductor deposition equipment: the batch equipment and the single-wafer equipment. The batch film deposition equipment processes about 25 to 100 wafers at the same time. A single-wafer film deposition equipment processes wafers one by one. As shown in Fig. 1, the batch film deposition equipment is covered by a vertical furnace type heating unit. Wafers are arranged vertically like a high-rise building. To eliminate even the slightest asymmetry of the process chamber, wafers are slowly processed while rotating the wafers. The process takes time (2 to 10 hours) and achieves highly homogeneous film thickness. Here, a film is also deposited on the reverse side of the wafers. An additional step in the process is required to remove the deposited film before moving on to the next step. Various types of equipment are required to increase the throughput.

Meanwhile, the single-wafer film deposition equipment processes a wafer far more quickly (in about a few minutes) than the batch equipment. It processes a wafer placed on a heater, and no film is deposited on the reverse side. This makes it possible to move on to the next step smoothly.

The various semiconductor manufacturers take advantage of the characteristics of both batch and single-wafer film deposition equipment for different steps. Previously, the batch film deposition equipment had an advantage in

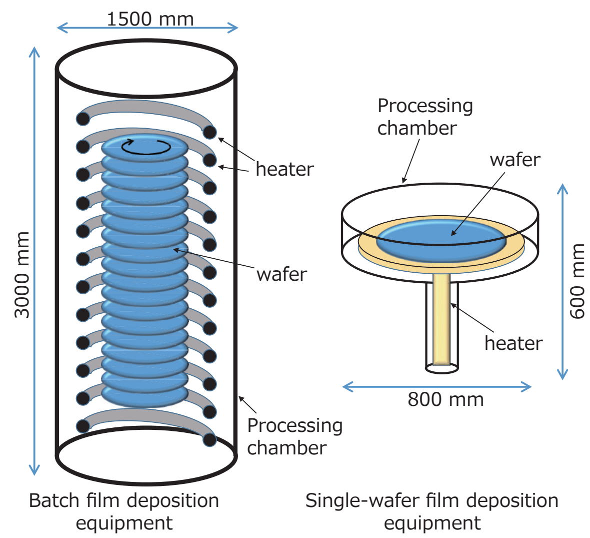


Fig. 1. Schematic drawings of the batch film deposition equipment and the single-wafer film deposition equipment

terms of performance, and as a result, the single-wafer film deposition equipment was hardly ever used for steps that required particularly high precision. However, in line with the recent increase in memory capacity, the number of repetitive steps in the front-end process has increased dramatically. The single-wafer film deposition equipment, whose throughput is high, has started to attract attention. There has been growing demand for high-quality deposition using the single-wafer film deposition equipment. To achieve highly homogeneous deposition, it is essential to achieve uniform temperature distribution on the wafer surface.

3. Overview of SumiTune

SumiTune is an abbreviation of Super Multi Intelligent heating Tune system. The system consists of the SumiTune Heater and the SumiTune Controller (Fig. 2). In dry etching systems, multi-zone heaters and multi-zone controllers have been embodied as electrostatic chucks equipped with a wafer chucking function. Many systems have been developed and operated to control the temperature distribution with more than 100 zones.

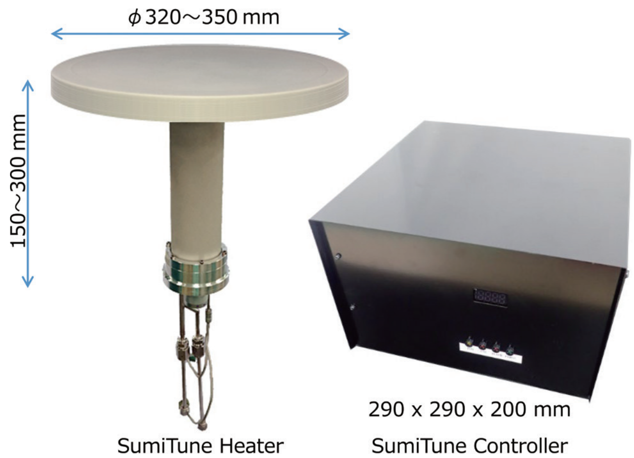


Fig. 2. Appearance of SumiTune

In the film deposition equipment, since it was previously difficult to develop multi-zone heaters due to the use of corrosive gases, the number of zones was limited to three. Metals used for the electrodes of the heating circuit of heaters are susceptible to corrosive gases. Thus, these metals are covered with highly anticorrosive AlN materials. As shown in Fig. 3, the equipment uses a mushroom-shaped AlN heater consisting of an AlN shaft that houses and protects the electrodes and a plate that contains a heating circuit. Increasing the number of control zones of an AlN heater is equivalent to increasing the number of electrodes of a heating circuit. To house many electrodes, it is necessary to increase the shaft diameter. An increased shaft diameter causes the bonding part with the plate to crack due to thermal stress caused by the temperature difference between the upper and lower parts of the shaft. Thus, there are restrictions on the shaft diameter, and the number of electrodes is inevitably limited. Only heaters with up to three zones (six electrodes) have been put on the market.

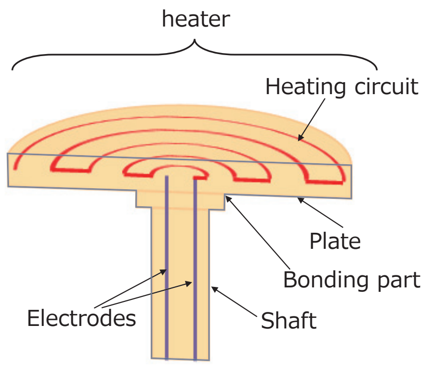


Fig. 3. Schematic structure of a general film dep-osition heater

In conventional heaters, two or more zones were arranged concentrically, as shown in Fig. 4 (a). The temperature could be adjusted uniformly in the radius vector (r) direction. However, these heaters could not cope with the temperature distribution unevenness in the circumferential (θ) direction attributed to the asymmetry of the equipment and surrounding environment. Thus, there were limitations on the scope of temperature distribution uniformity on the wafer surface.

We have developed a six-zone heater with 1-1-4 zoning to arrange three zones in the r direction and four zones in the θ direction, as shown in Fig. 4 (b). Thermocouples were used for temperature control, but they could be housed only inside the shaft to ensure corrosion resistance. Even if a multi-zone arrangement was achieved, it was difficult to monitor the temperature of each zone. We found that it was possible to control the temperature of the six zones by controlling the power efficiently and accurately. We have developed a compact controller that can be housed in the manufacturing system.

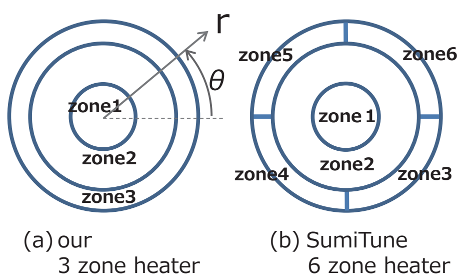


Fig. 4. Image of zones

3-1 Features of the SumiTune Heater

Notably, to arrange multiple zones in the θ direction in the circumferential zone, the lead wires to the heating circuits must be arranged at different layers within the heater. Thus, tungsten (W) paste was printed with high precision by using screen printing technology to form a circuit for each zone on multiple AlN substrates (see Fig. 5). Next, multiple AlN substrates were stacked to sandwich the circuit, and hot press bonding was performed, as shown in Fig. 6. This is how we fabricated the heater main unit with embedded circuits. It was easy to arrange circuits at different layers within the heater because zones could be assigned to multiple layers. The electrodes to power the circuit were processed and a shaft was attached. Finally, the workpiece was cut into the product shape.

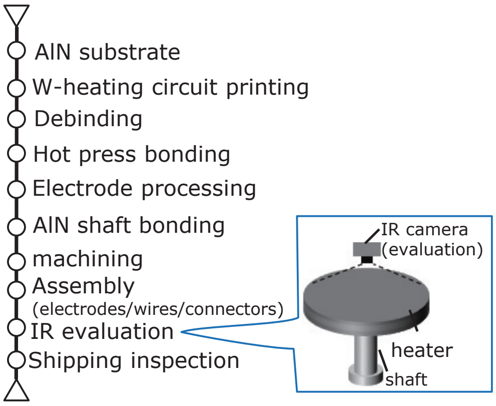


Fig. 5. Manufacturing process of our AlN heater

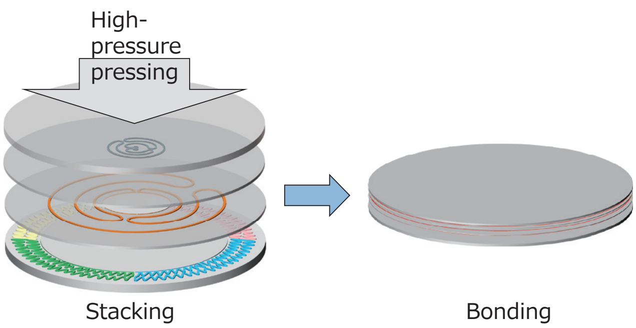


Fig. 6. Image of hot press bonding

A single heating unit circuit requires two electrodes*2 (i.e., a positive electrode and a negative electrode) to supply electricity. This means that one heating unit circuit is required for each of the six zones (12 electrodes in total). It was necessary to reduce the number of electrodes due to the restriction of the shaft diameter. It was also laborious to connect each electrode to lead wires outside the equipment. To enable one-touch connection, we designed a heater equipped with a multi-electrode one-touch joint connector in a flange under the shaft. By taking into account the permissible current of the connection pins of connectors to be used, the heating unit circuits for zone 1, zone 2, and zones 3 to 6 were arranged in three different layers, in the height direction from the top surface, to avoid interference between the zones, as shown in Fig. 7. We designed a heater to control six zones using nine electrodes in total: negative electrodes arranged as a common electrode for zones 1 and 2, zones 3 and 6, and zones 4 and 5, respectively, plus six positive electrodes for zones 1 to 6. The optimal zone distribution capable of supporting various temperature distribution patterns, as shown in Fig. 8, was determined using high-definition patterns based on computer simulation analysis.

Regarding the temperature uniformity range (difference from the mean value of the maximum value and minimum value) for the flat temperature distribution

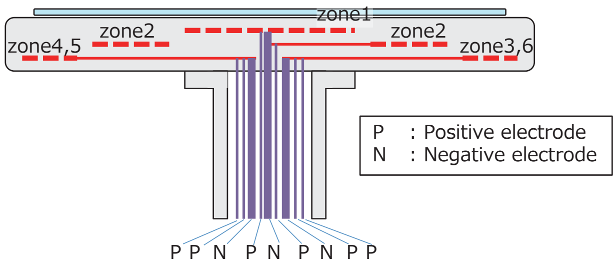


Fig. 7. Image of wiring and electrodes

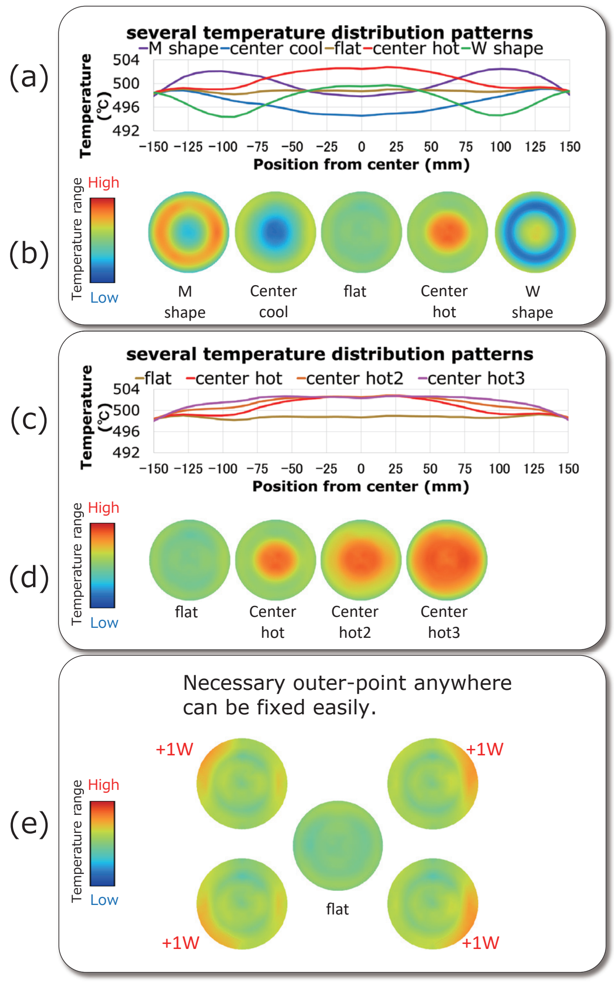


Fig. 8. Results of CAE analysis of heater temperature distribution

pattern, we aimed to attain a temperature uniformity range of ±0.5°C or less for the heater surface temperature in order to attain the market requirement of ±1.0°C or less. The final specifications of the SumiTune Heater are shown in Table 1.

Table 1. Specifications of the SumiTune Heater

Material	AlN 99.6%
Temperature range	Room temperature to 650°C
Heating/cooling rate	5°C/min
Rated output	AC200 V / 30 A
Supported wafer size	12 inch (300 mm)
Standard size	Diameter: φ320 ~ 350 mm Height: 150 ~ 300 mm
Number of zones	6
Supported thermocouple	type-R or K
Temperature uniformity range within φ300 (49 points, @500°C)	Specifications ≤ ±1.0°C [Capacity ±0.5°C]
Temperature uniformity range within each zone (@500°C)	≤ ±0.5°C
Energizing connector	One-touch connection with the controller is enabled by the special one-touch assembly connector and special cable.

3-2 Features of the SumiTune Controller

To control the temperature in each zone, it is considered as essential to have the means to measure the temperature of each zone accurately. Regarding the heaters for the coater developer system, which offers flexibility in the arrangement of electrodes, one thermometer is installed in the center of each zone to achieve temperature control.

For the film deposition equipment, it was virtually impossible to ensure corrosion resistance when installing thermocouples and optical sensors in the zones outside the shaft. We found that a certain temperature distribution can be maintained by maintaining a certain power distribution. For zone 1, the thermocouple installed in the center of the heater was subject to temperature control by PID control*[3]. For other zones, we designed a mechanism to adjust the temperature of each zone by controlling the power at a predetermined power ratio against the power for zone 1. To achieve high-precision temperature control of 0.1°C, we aimed to develop a controller capable of controlling the power ratio with a resolution of 0.001 to ensure a power ratio control precision of 0.01. In terms of the working principle, the power ratio can be controlled by linking a commercially available temperature controller with a power ratio controller. However, this does not meet the requirements of controllability, response, precision, and compactness. We set a goal to develop the SumiTune Controller with the specifications shown in Table 2 as a temperature and power controller for the SumiTune Heater.

3-3 Features of the SumiTune System

The main features of the SumiTune System are as follows.

[1] Capable of achieving a flat temperature distribution pattern with a temperature uniformity range of ±0.5°C as well as various temperature distribution patterns

Table 2. Specifications of the SumiTune Controller

Supported thermocouple	type-R or K
Control temperature range	Room temperature to 650°C
Input rating of the load circuit	AC208 V ±10% 60 A 60 Hz/50 Hz
Input rating of the control circuit	AC120 ~ 230 V 2 A 60 Hz/50 Hz
Number of zones	6
Number of output terminals	9ea (ch1 ~ 6,COM1 ~ 3) + GND
Output rating	AC200 V / 60 A (There is a limitation for each zone.)
Temperature control method	PID control for Zone 1
Power control method	Phase control of zero-cross detection
Settable power ratio	0.000 ~ 9.999 v.s. zone 1
Resolution of temperature/power/voltage/current	0.01°C / 0.1 W / 0.01 V / 0.01 A
Communication method	RS-485, EtherCAT (switchable by a dip switch)
Size/weight	290 × 290 × 200 mm / 11 kg
Safety mechanism	External interlock function
Applicable guidelines and approval awarded	• Guidelines for safety of semiconductor manufacturing systems (SEMI S22) • International standard for product safety of control boards of controllers (EN 61010-1)

[2] Capable of coping with asymmetry factors in the deposition processing chamber environment

[3] Capable of reducing the development period and costs

3-3-1 Capable of achieving various temperature distribution patterns

The SumiTune System can achieve not only a flat temperature distribution pattern with a temperature uniformity range of ±0.5°C, as shown in Fig. 8 (a) and (b), as well as M-shaped, center-cool, center-hot, and W-shaped patterns. It can also flexibly change the range of the center-hot pattern, as shown in Fig. 8 (c) and (d). In general, the power ratio in and outside a heater must be changed depending on the temperature range and film type used. A single system can cope with various deposition processes by enabling various temperature distribution patterns.

3-3-2 Capable of coping with asymmetry factors based on the 1 W adjustment

In temperature-sensitive processes, conventional heaters could not adjust the wafer temperature distribution based solely on the adjustment of the heater temperature distribution (adjustment of deposition distribution in the actual process). Such fine adjustment required optimization of the arrangement of the shower head holes for supplying reactant gases, and adjustment and refabrication of gas diffusion plates immediately before the shower head. SumiTune ensures good power controllability. As shown in Fig. 8 (e), power adjustment of 1 W in the circumferential zone is equivalent to temperature adjustment of approximately 0.02°C at around 500°C, making it possible to fine-adjust the temperature distribution. It also enables the fine-adjustment of partially inhomogeneous deposition distribution in the θ direction attributed to the asymmetry factors of the deposition processing chamber environment (e.g., positions of the wafer loading port, gas exhaust line port) as shown in Fig. 9.

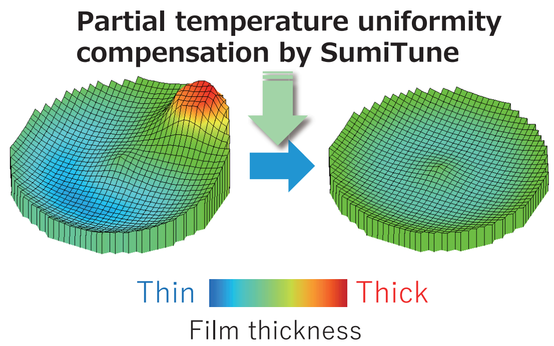
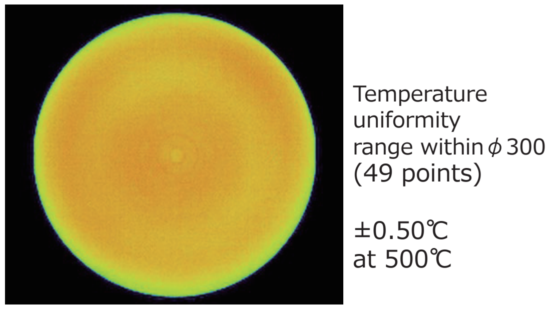


Fig. 9. Image of deposition distribution improvement by SumiTune



	zone1	zone2	zone3	zone4	zone5	zone6
Power (W)	412	561	210	210	210	210
Power ratio	1	1.363	0.510	0.510	0.510	0.510

Fig. 10. IR image of surface temperature distribution of the SumiTune Heater

3-3-3 Reduction of development time and costs

Conventionally, it takes three months to design and manufacture a heater suitable for the environment of a customer's facility, and another one month to verify the process at the customer's facility. Furthermore, if improvements are needed, the same amount of time is spent for remanufacturing and re-evaluating, and therefore design changes can only be made about three times a year. SumiTune can adapt to various environments. Once the first heater is designed and manufactured, it is possible to evaluate various conditions in the subsequent film formation verification by the customer and eliminate the need for the improvement (remanufacturing / re-evaluation) of the heater. This achieves significant reduction in the time required for the development, making it possible to minimize the number of evaluations for trial and error using wafers and to contribute to substantial reduction of the development costs.

4. Development Results

RS-485 communication, whose performance is well established, was used for the programmable logic controller (PLC) for controlling the controller to increase reliability. The system also supported EtherCAT*4 for real-time communication. EtherCAT is recognized as the communication standard for semiconductor manufacturing systems in the SEMI*5 guidelines. Regarding the power control precision of the controller, precision in units of 0.001 was achieved with the power ratio indication resolution in units of 0.002. This ensured temperature controllability of 0.02°C in terms of temperature, achieving a temperature uniformity range of ±0.5°C at 49 points of heater surface temperature in the IR evaluation*6 at a heater temperature of 500°C (Fig. 10). A temperature uniformity range of ≤ ±1.0°C or less was achieved as the specifications for users. As shown in Table 3, the concentric temperature uniformity range is less than ±0.5°C, and the zone temperature uniformity range is less than ±0.4°C. It was found that the SumiTune System has a temperature uniformity performance suitable for next-generation deposition.

Table 3. Results of temperature uniformity evaluation

Heater temperature		500°C
Temperature uniformity (°C)		±0.50°C
Concentric temperature uniformity range	φ100	±0.21°C
	φ200	±0.30°C
	φ300	±0.41°C
Zone temperature uniformity range	zone1	±0.34°C
	zone2	±0.30°C
	zone3	±0.21°C
	zone4	±0.35°C
	zone5	±0.18°C
	zone6	±0.14°C

5. Conclusion

SumiTune has made it possible to make partial fine adjustments of temperature distribution, which was not possible with conventional deposition heaters with two or three zones. The system can achieve high temperature uniformity depending on the chamber environment and meet the need for miniaturization of the circuit wiring. Evaluations have already started at semiconductor system manufacturers and semiconductor manufacturers. The deposition distribution is expected to be improved significantly by fine tuning. These manufacturers are studying the possibility of using the system in place of the batch deposition equipment.

There has been a growing need for miniaturization of the wiring. Even with six-zone (1-1-4) control it is likely to be difficult to meet this need in several years' time. We have therefore been developing a nine-zone (1-4-4) control system, which is currently in test operation.

- SumiTune is a trademark or registered trademark of Sumitomo Electric Industries, Ltd.
- EtherCAT is a trademark or registered trademark of Beckhoff Automation GmbH.

Technical Terms

*1 GPU: Abbreviation of graphics processing unit. GPUs were originally used for rendering of graphics. Recently, they have attracted attention for their parallel processing capability and have been used for artificial intelligence and computer simulation processing.

*2 Electrode: In general, alternating current is used for the film deposition equipment. For convenience's sake, the terms "positive electrode" and "negative electrode" (which are the terms used for direct current circuits) are used to differentiate the electrodes.

*3 PID control: Abbreviation of proportional-integral-differential control. This is a type of feedback control in control engineering. Input values are controlled based on three factors: deviation between the output value and target value (P), integral (I), and differential (D).

*4 EtherCAT: This is the real-time communication standard recognized as a communication standard for semiconductor manufacturing systems under the SEMI guidelines.

*5 SEMI: Abbreviation of Semiconductor Equipment and Materials International.

*6 IR evaluation: This is one of the means to scan the difference in the wavelengths of infrared rays, which change depending on the temperature, using an infrared camera to measure the temperature distribution.

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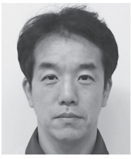

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