Site Flatness Measurement System with Accuracy of Sub-nanometer Order for Silicon Wafer

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A new system using a heterodyne interferometer has been developed to measure site flatness with an accuracy of sub-nanometer order for 300 and 450 mm wafers. This system is based on a spiral scan method, which enables the measurement of global flatness and site flatness. It is also possible to measure SFQR and ESFQR with 0.5 nm (σ) repeatability in an environment with as much as 5 Gal of floor vibration. This paper outlines the system and describes the experimental results for repeatability concerning global flatness and site flatness. Actual measurements turned out a GBIR of 0.68 nm (σ), SFQR of 0.33 nm (σ) and ESFQR of 0.39 nm (σ). Next, referring to the results of the measurement of actual wafers, it explains how this new system is effective in managing the process.

Introduction

The structures of silicon semiconductor devices are being miniaturized, allowing only small process margins for lithography. In lithography processes, focusing is conducted per each site within the surface of a chucked wafer, involving tilting to make each focal plane perpendicular to the optical axis. A wafer having a site thickness with variations greater than the focal depth of the optical system can cause failure attributable to defocusing. The local flatness of each site is referred to as "site flatness" and must have a dimension at the same level as the minimum working size of devices. The minimum working size has currently become 25 nm and has been refined at a pace of approximately 5 nm per year. There are trial manufacturing lines being planned for a line width of ten-odd nanometers, which has led to the need for an system that can measure site flatness with an accuracy in the order of sub-nanometers.[1)]

In general, shape measurement systems with sub-nanometer accuracies are subject to various disturbances, such as environmental vibrations, and can only be installed at limited locations. Flatness-inspection processes and facilities, on the other hand, require a system that enables measurement with high accuracy without preparing a special environment.

Regarding the size of wafers, φ300 mm wafers are mainly being used, and production processes for φ450 mm wafers are being studied.

Recognizing the rising interest in highly accurate site-flatness inspection, Kobelco Research Institute, Inc. and Kobe Steel have developed a system (hereinafter, "the present system") for measuring site flatness with an accuracy of sub-nanometer order (**Fig. 1**[2)]). The present system has improved vibration resistance and is designed for 300 mm and 450 mm silicon wafers after mirror surface polishing. This paper first summarizes the site flatness, then outlines the present system and finally describes actual measurement.

1. Indices of flatness

The indices of flatness include global flatness and site flatness (**Fig. 2**[3)]). Global flatness is typically represented by the global backside ideal range

Fig. 1 LSW-3010FE (Site flatness measurement system with an accuracy of sub-nanometer order for silicon wafer)[2)]

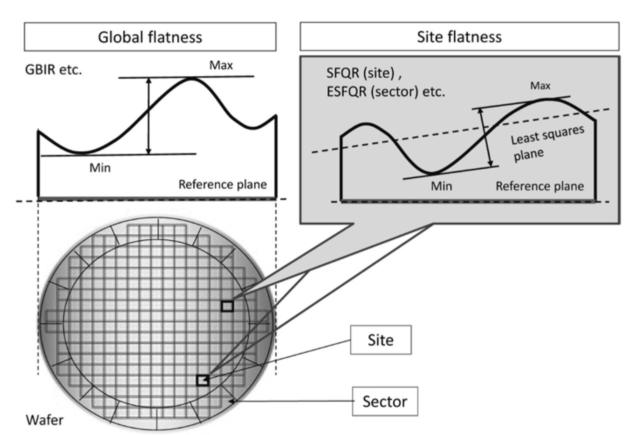

Fig. 2 Definition of GBIR, SFQR, ESFQR[3)]

(GBIR), which evaluates the thickness variation of an entire wafer. The GBIR is defined by the difference between the maximum and minimum values of thickness distribution. Site flatness, on the other hand, is typically represented by the site front least-squares range (SFQR) and edge site front least-squares range (ESFQR.) In SFQR, the entire surface of a wafer is separated into sites, each corresponding to an IC chip, and thickness variation is measured within each of these sites. The ESFQR evaluates the areas along the edge of a wafer where flatness tends to deteriorate compared with the inner wafer surface. The belt-like circumferential zone of a wafer is separated into equally-spaced sectors (as shown in Fig. 2) and the thickness variation in each sector is measured. The SFQR and ESFQR are each defined by the difference of maximum and minimum values that are determined from the distance from the reference plane that is obtained by the least-square method from the thickness distribution for the respective sector.

These indices are provided as indicators that affect the yield of the lithography process and are used also in the specifications for wafer trading. Hence, these indices, and their inspection accuracy as well, are regarded as important by wafer manufacturers and device manufacturers.

2. Measurement system

2.1 Measurement principle and advantage

Non-contact flatness measurement is usually conducted by means of electrostatic capacity, optical interference, triangulation, etc. The electrostatic capacity method, in particular, allows measurements of wafers with rough surfaces. Having an accuracy of several tens to a hundred nanometers depending on the objective distance and measurement range, it has been widely used in flatness inspection systems.[4)] To achieve measurement with accuracy better than several ten nanometers, optical interferometry involving, for example, Fizeau interferometers and oblique-incidence interferometers, is generally used. Although these methods are applicable only to certain surface conditions of measured objects, they have the advantage of high accuracy. With the aim of achieving reproducibility in the order of sub-nanometers, the present system adapts the heterodyne interference method, in which shapes are measured by an optical probe. The following describes the measurement principle:

A wafer is rotated in the horizontal plane in the gap between a pair of sensor heads (optical probe), vertically disposed face to face with each other. The wafer is also moved in a linear direction such that the scanning is performed in a spiral motion. The wafer is edge-supported on a stage that can both rotate and move linearly, which governs the motion of the wafer (**Fig. 3**). During scanning, the apparatus measures the in-plane displacement change between the upper sensor head and the front surface of the wafer (ΔD_F; reference being made to the starting point of the measurement). Also measured is the displacement change between the lower sensor head and the back surface of the wafer (ΔD_B). Since the sensor heads are spaced at a constant distance, adding the changes of displacement measured by the two sensor heads enables the calculation of thickness variation (ΔT) in the plane.

The measuring principle of a displacement meter based on heterodyne interferometry (hereinafter, "heterodyne interferometer") is shown in **Fig. 4**. In the laser source, a laser beam is split into two laser beams, one modulated to a frequency of f and the other modulated to $f + \Delta f$, which are individually guided to the sensor heads. The two laser beams are incident on both the measurement surface of

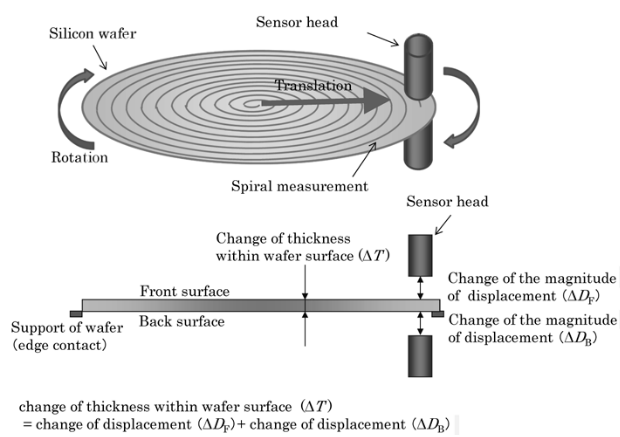

Fig. 3 Schematic of measurement part

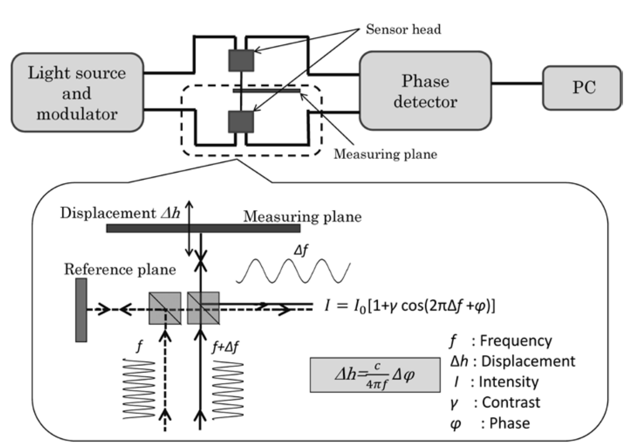

Fig. 4 Measuring method

the wafer and the reference surface contained in the sensor heads, and the reflected light is guided into the phase detector via optical fibers. The composite intensity of the two reflected light is brightness modulated by a modulated beat frequency of Δf to turn into interference signal I expressed by Equation (1):

$$I = I_0 \left[1 + \gamma \cos(2\pi \Delta f t + \varphi) \right] \quad \cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots \quad (1)$$

wherein I_0, intensity sum of the two light; γ, contrast; φ, phase of combined light; and t, time. The phase of the interference signal is determined by the distance between the measurement surface and reference surface, and the relation between the amount of displacement variation on the measurement surface and the phase difference is given by Equation (2):

$$\Delta h = \frac{c}{4\pi f} \Delta \varphi \quad \cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots \quad (2)$$

wherein: Δh, displacement variation; $\Delta\varphi$, phase difference: c: light speed. The amount of displacement variation at the measurement surface is given by detecting the phase difference $\Delta\varphi$, and calculating Equation (2). A heterodyne interferometer measures the phase change of interfering light and, hence, has the advantage of being immune to the change in light intensity in principle.[5)]

In addition, the heterodyne interferometer of the present system comprises one laser source for both the upper and lower sensor heads, as well as a common path, such that the drift caused by the change in ambient temperature is suppressed. Also, a polarization-maintaining optical fiber was adapted for the optical transfer between the units such that the interference signals are not affected by light phase and polarization disturbed by the pressure and/or vibration applied to the optical fiber itself. A simulation analysis was conducted on the structure of the sensor heads and their supports so as to minimize the measurement errors caused by the vibrations of the drive unit and floor. The results were reflected in the design. Furthermore, the effect of sound on the measured values was evaluated experimentally for the selection of the cover material and shape of the sensor heads. Various measures were thus taken to make the system immune to any conceivable disturbances, such as temperature change, vibration and sound.

2.2 Structure of flatness measurement unit

In a thickness measurement system having a pair of facing probes, the change in the spacing between the probes can become an error factor in the measured values. Hence, in addition to suppressing vibrations caused by the drive unit and other external factors, the system must have a structure with a minimum deformation due to the gravity-center shift of the stage. **Fig. 5** shows the construction of the present system. The rotary stage is driven by a hollow motor with air bearing, while the linear stage is driven by a linear motor with air sliders, to minimize the vibration of the stages during operation. The base and sensor holders included in the measurement unit are made of granite, which provides excellent vibration damping and has a small coefficient of thermal expansion, so as to suppress the infinitesimal deformation of the structure due to vibration and thermal expansion. In general, vibration absorbers based on air springs are often used for removing vibration from the floor. These absorbers, however, usually have a resonance region in the several Hz range, which may change the alignment of the system. Hence the present system comprises an active vibration isolator, which detects vibration and change in the alignment to perform feedback control, and successfully suppresses the low-frequency resonance and alignment change.

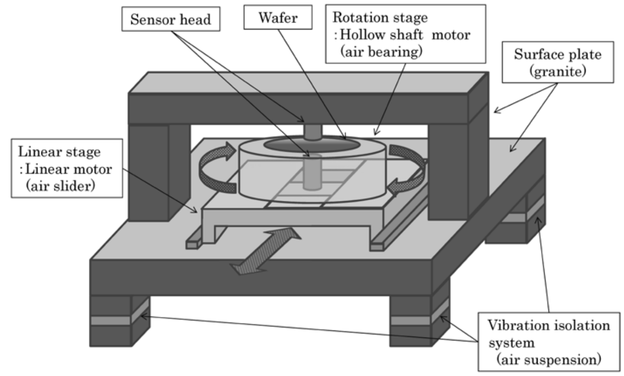

Fig. 5 Measurement system composition

The upper and lower sensors may be misaligned, due to the alignment error and temperature change, causing errors in the thickness values measured, as well as system differences and the long-term fluctuation of measured values. In order to adjust the sensor positions, a biaxial linear-moving horizontal stage, along with an algorism for the automatic control, has been developed. Periodic calibration using this stage can suppress the measurement errors.

3. System performance evaluation

3.1 Repeatability evaluation

Using the present system, a 300 mm wafer was measured for its GBIR, SFQR, and ESFQR, each 10 times, to evaluate the repeatability.

The results of the GBIR measurement are shown in **Fig. 6**. The standard deviation (σ) is 0.68 nm. Against the total thickness variation for the wafer of 649.2 nm (on average), the results demonstrate the repeatability of 1 nm or better. The measured values vary randomly without any distinguishing trend, such as monotonic increase, in the characteristic variation. **Fig. 7** depicts the standard deviation (σ) of the measured SFQR values plotted for the frequency distribution for the number of sites. The conditions for calculation are: size of site, 26 x 8 mm; site offset, (0,0); and the total number of sites, 336. The standard deviations (σ) for all the sites are 0.33 nm on average; 88.3% of the sites have standard deviations of 0.5 nm or smaller; and all the sites have standard deviations of 1 nm or smaller. Likewise, **Fig. 8** depicts the standard deviation (σ) of the measured ESFQR values plotted against the frequency distribution for the number of sites. The conditions for calculation are: sector length, 30 mm; sector angle, 5 degree; and the total number of sites, 72. The standard deviations (σ) for all the sites are 0.39 nm on average, 87.9% of sites have standard deviations of 0.5 nm or smaller, and all the sites have standard deviations of 1 nm or smaller.

Comparison of the distributions of standard deviation (σ) between SFQR and ESFQR indicates that SFQR has a greater number of sites having standard deviations (σ) of 0.25 nm or smaller. This is considered to be attributable to the area of each site that is 70% smaller than a sector making the measurement time for each site shorter, which suppresses the errors having long-term compositions. A similar explanation may hold for the repeatability of SFQR and ESFQR, which is better than that of GBIR.

The above results confirm that, in addition to global flatness, the site flatness of the inner and near-the-edge surface can be measured with an accuracy of sub-nanometer order, which was the object of this study.

3.2 Actual measurement

The present system was used for the measurement of two practical wafers (samples A and B.) **Fig. 9** depicts 2-dimensional maps of thickness, as well as the thickness distribution measured along each line (the arrows in the figure.) The GBIR for sample A was 0.609 μm, while that for

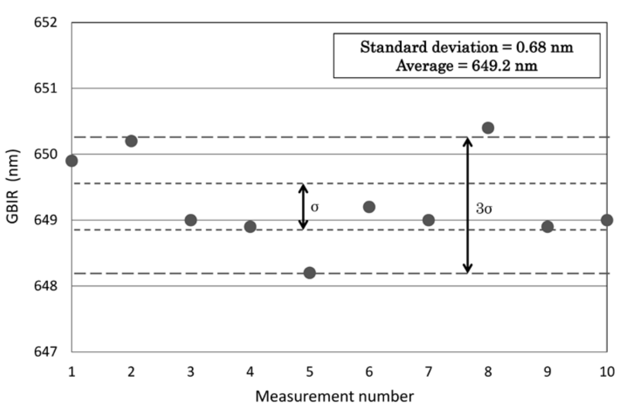

Fig. 6 Repeatability of GBIR

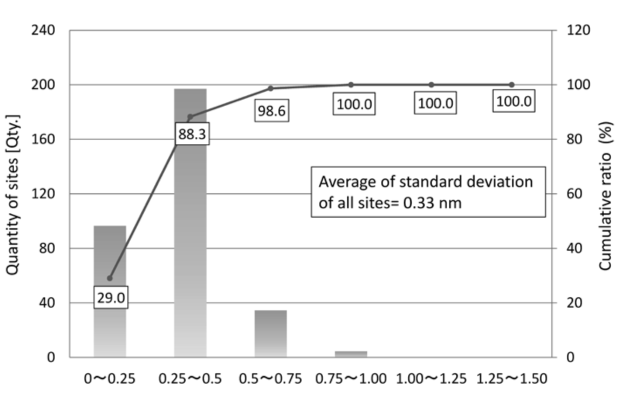

Fig. 7 Repeatability of SFQR

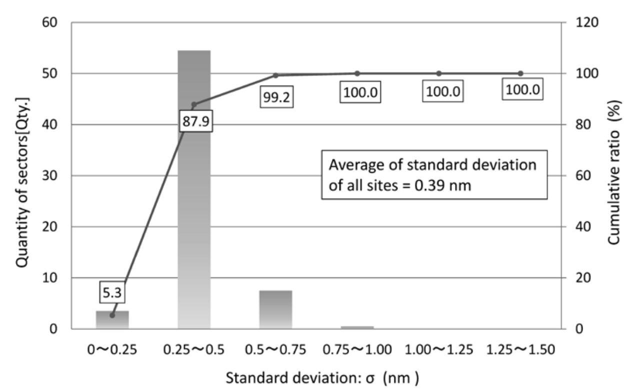

Fig. 8 Repeatability of ESFQR

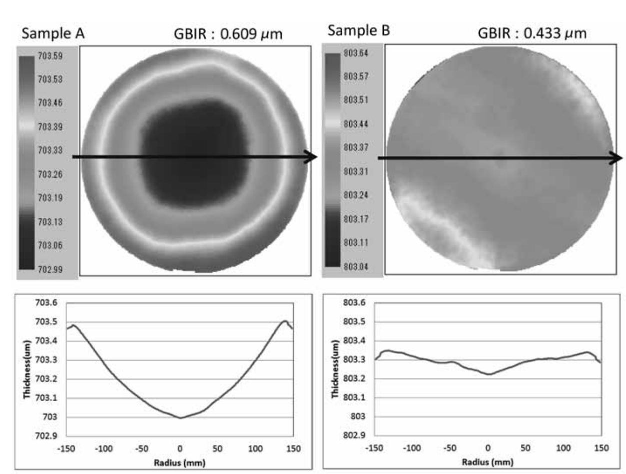

Fig. 9 2 D map of sample A, B

sample B was 0.433 μm. In general, the flatness of a wafer tends to deteriorate near the circumference rather than the central region.[6] The thickness distribution measured along one line shows a significant thickness change for each of the wafers, verifying the measurement of thickness distribution in submicron order.

Fig.10 provides SFQR site maps. Each map is a gray scale image of 20 nm pitch with darker gray representing greater values, and only the sites with values of 10 nm or smaller are represented by white. Focusing on the central region of each wafer, sample A is mostly occupied by sites with SFQRs of 20 nm or smaller, while sample B has a number of sites with SFQRs exceeding 20 nm. Hence the average value is smaller for sample A; 26.9 nm for sample A and 30.5 nm for sample B. Each sample has near-the-edge sites whose values are greater than those in the corresponding central region and are close to 100 nm. Comparing the SFQR Max, sample A has a value of 135.5 nm and sample B has a value of 107.9 nm, sample A having a value greater by approximately 30 nm. **Fig.11** shows the results of ESFQR measurement conducted on the same wafers to study the details near the respective edges. The vertical axis represents the ESFQR values measured, while the horizontal axis represents the angles of the sectors in the circumferential direction. The ESFQR average values are 335.4 nm for sample A and 466.2 nm for sample B, showing that sample A has smaller values as a whole. The above evaluation indicates that sample A has smaller thickness variation near the edge, while the thickness variations in the circumferential direction are similar for both the wafers.

As has been described thus far, the present system can clearly detect thickness variations of practical samples in micron to nanometer order. Their flatness features have been clarified by several evaluation techniques.

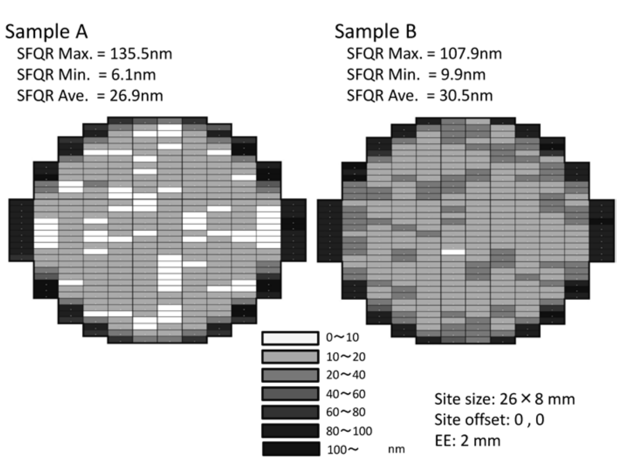

Fig.10 SFQR site map of sample A, B

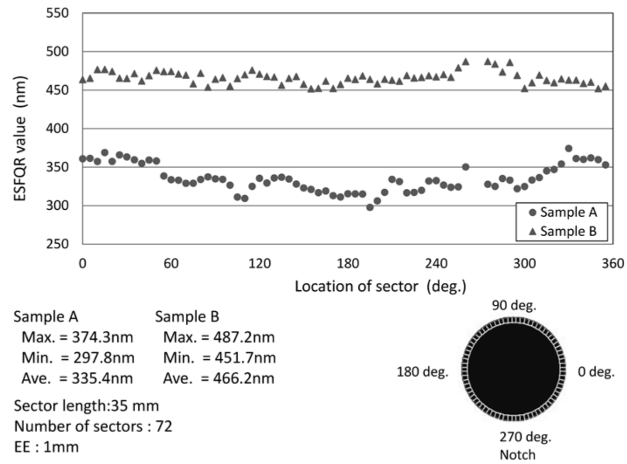

Fig.11 Relationship between ESFQR and sector angle of sample A and B

3.3 Discussions

Actual measurements have confirmed the repeatability of 0.68 nm (σ) for GBIR, 0.33 nm (σ) for SFQR and 0.39 nm (σ) for ESFQR (see 3.1.) These results demonstrate that the present system is capable of measuring wafer thickness with an accuracy of sub-nanometer order. The present system satisfies the measurement accuracy required for a site-flatness inspection system and can evaluate the wafers used for ten-odd nanometer design rule, which is expected to be launched in volume.

The present system may be used for the optimization of wafer polishing conditions. For example, the roll off of wafer-edges, occurring in the process of etching, grinding and polishing, may be improved by visual means based on 2 dimensional mappings and line profiles, as well as by quantitative evaluation by ESFQR measurements, as demonstrated for samples A and B (see 3.2.) Also, among other things, flatness deterioration due to malfunctioning wafer polisher may be detected, allowing the use of feedback in various manufacturing processes.

The specifications of the present system are listed in **Table 1**. It is less susceptible to external vibrations and has been confirmed to achieve repeatability that equals to the one reported herein under a floor vibration of 5 Gal. The spatial resolutions are 1 mm or smaller for SFQR, and 0.5 nm or smaller for ESFQR. The measurement time is 60 sec/wafer or less (for SFQR measurement) including the wafer transfer time by edge handling.

Table 1 Standard specification of developed measurement system

Wafer / Size	Silicon monocrystalline wafer (polish) / 300 mm
Wafer thickness	650～850 μm
Cassette / Transportation	FOSB, Open, FOUP etc. / Edge handling
Measurement method	Laser interferometer (flatness, bow/warp) Laser displacement meter (center thickness)
Scan mode	Spiral scan : R direction ; 0.5 , 1 , 2 mm pitch θ direction : ≦1 mm pitch
Measurement item	Global flatness : GBIR, GFLD, GF3D, GFLR, GF3R Site flatness : site ; SBIR, SFLR, SF3R, SFQR, SBID, SFLD, SF3D, SFQD sector ; ESFQR, ESFQD Shape : bow/warp Thickness : center thickness etc.
Repeatability(σ)	GBIR : ≦3 nm (typ. : 1 nm) SFQR : ≦1 nm (typ. : 0.5 nm) ESFQR : ≦1.3 nm (typ. : 0.5 nm) bow/warp : 1.2+ (warp/100) μm
Tact time	≦ 60 s/wafer
Size of device / Weight	1,970 × 2,990 × 2,200 mm (W,D,H) / 4,500 kg (approx.)
Temperature	23℃±1℃
Environment	Vibration of floor : ≦5 Gal, Clean room : Class1000 or More
Application	Edge rolloff, Resistance, PN judgment, ID reading, Diameter FFU, Load port, OHT, SECS/GEM etc.

Conclusions

A site flatness measurement system with sub-nanometer order accuracy has been developed for the post-polishing inspection of silicon wafers. The system comprises a heterodyne interferometer, a stage/base having excellent anti-vibration performance, and a highly functional vibration absorber. The repeatability (σ) of global flatness and site flatness was 0.68 nm for GBIR, 0.33 nm for SFQR and 0.39 nm for ESFQR, as per actual measurements. Flatness evaluation indices, such as SFQR and ESFQR, were compared for two wafer samples, which revealed their flatness features. The present system thus has been verified to be effective for various process controls.

The present system with enhanced vibration resistance is expected to be used for various wafer production processes and research applications so as to contribute to the manufacturing of high-quality wafers.

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