Precision Nanometrology and its Applications to Precision Nanosystems

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In this paper, a new field of metrology called "precision nanometrology" is presented. The "precision nanometrology" is the result of evolutions of the traditional "precision metrology" and the new "nanometrology". "Precision nanometrology" is defined here as the science of dimensional measurement and motion measurement with 100 nm to 0.1 nm resolution/uncertainty within a range of micrometer to meter. The definition is based on the fact that nanometrology in nanoengineering and the precision industries, such as semiconductor industry, precision machine tool industry, precision instrument industry, is not only concerned with the measurement resolution and/or uncertainty but also the range of measurement. It should also be pointed out that most of the measurement objects in nanoengineering have dimensions larger than 1 micrometer. After explaining the definition of precision nanometrology, the paper provides several examples showing the critical roles of precision nanometrology in precision nanosystems, including nanometrology system, nanofabrication system, and nanomechatronics system

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1. Introduction

Although "nanometrology" is a term which has been used since the late of 1980s [1], its definition still remains unclear. In 1992, E. C. Teague of NIST defined "nanometrology" as the science of measuring the dimensions of objects or object features to uncertainties of one nanometer or less [2]. Recently, the Working Group on Dimensional Metrology (WGDM7 DG) of the Consultative Committee for Length (CCL), recommended the definition of "nanometrology" as the science of measurement of the dimensions of objects or object features, separations or displacements in the range from 1 nm to 1000nm [3]. Comparing the two definitions, it can be seen that the former focuses on the uncertainty of the measurement result, while the latter on the size of the measured object or the measurement range.

On the other hand, precision dimensional measurement or simply called precision metrology has a long history started with the inventions of micrometer (J.Watt 1772), gage block (C Johansson,1896), interferometer (A.Michelson 1881) [4,5]. It established the fundament for the Industrial Revolution and contributed greatly to modernize industries based on interchangeable manufacturing. At present, it is still playing an important role in science and technology. The term "precision" best reflects the nature of precision metrology, which is often related with the ratio of resolution/uncertainty to range[6,7].

As can be seen in Fig. 1, the "nanometrology" field is keeping to expand its measurement range while the "precision metrology" keeping to improve its resolution/uncertainty. The trends of the "precision metrology" and the "nanometrology" result in the generation of a new field of metrology, which is proposed in this paper as "precision nanometrology". As shown in Fig. 1, the "precision nanometrology" is considered as the science of dimensional measurement and motion measurement with 100 nm to 0.1 nm resolution/uncertainty within a range of micrometer to meter. It is an engineering and industry-oriented definition rather than a precise and strict academic definition, which is based on the consideration that nanometrology in nanoengineering and the precision industries, such as semiconductor industry, precision machine tool industry, precision instrument industry, is concerned with both the measurement resolution/ uncertainty and the measurement range. The resolution/ range domain of precision nanometrology shown in Fig. 1 covers most of the practical measurement objectives in the precision industries. Similarly, nanosystems cored with the technology of precision nanometrology is here called as "precision nanosystems".

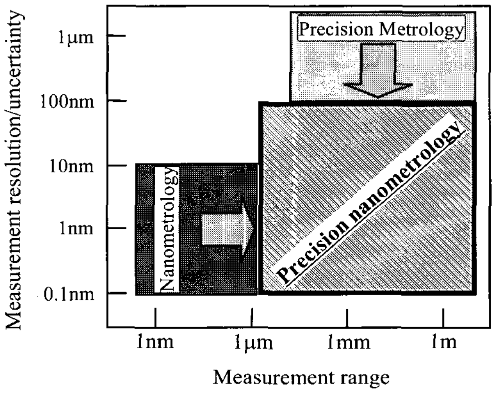

Fig. 1 The field of "precision nanometrology"

In the following, a couple of precision nanosystems, in which the technology of precision nanometroloy plays a critical roles, are demonstrated.

2. Precision nanometrology in precision nanomeasuring instruments

2.1 Precision nanometrology of roundness and spindle errors

Demand for workpiece out-of-roundness and spindle error measurement to nanometric accuracy is increasing. Separation of roundness error from spindle error is essential for satisfy the demand [8-10].

Fig. 2 shows the principle of a precision nanometrology technique called the mixed method [11-13] for roundness and spindle error measurement. A displacement probe and a slope probe[14,15] are used in this method. The angular distance between the two probes is 90 degrees. The workpiece is rotated around point O and the surface profile is scanned by the two probes that are spatially fixed. The displacement probe output $m_A(\theta)$ and the angle probe output $\mu_B(\theta)$ can be expressed as follows:

$$m_A(\theta)=r(\theta)+e_Y(\theta) \quad (1)$$

$$\mu_B(\theta)=r'(\theta+\pi/2)-e_Y(\theta_i)/R_r \quad (2)$$

where θ is the rotational angle of the workpiece. $r(\theta)$ is the workpiece roundness error, $e_Y(\theta)$ is the Y-directional component of the spindle error, R_r is the average radius of the workipiece.

A differential output $m(\theta)$, in which the roundness error is separated from the spindle error, can be denoted as

$$\begin{aligned} m(\theta) &= m_A(\theta)+R_r\mu_B(\theta) \\ &= r(\theta)-R_r r'(\theta_i+\pi/2) \end{aligned} \quad (3)$$

The transfer function of the mixed method, which represents the complex harmonic sensitivity of the differential output to the input roundness error, can be defined as

$$\begin{aligned} H(n) &=)M(n)/R(n) \\ &= 1+jne^{jn\pi/2} \end{aligned} \quad (4)$$

As can be seen from Fig. 3, there is no frequency at which the harmonic sensitivity approaches zero, indicating that the mixed method can correctly measure up to high frequency range, without suffering the problem of harmonic suppression, which is associated with conventional multi-probe methods [16]. The minimum harmonic sensitivity at n=2 is 2.24.

Fig. 4 shows the measured roundness errors of two separate measurements and the repeatability error between the two measured results. It can be seen that the roundness error is approximately 60 nm and the repeatability error is approximately 5 nm. The measured spindle errors of the two repeated measurements and the difference between them are shown in Fig. 5. The spindle error is approximately 800 nm, and the difference is approximately 140 nm. Vibration components are found in the spindle errors. Comparison of the results shown in Figs. 4 and 5 shows that the roundness error is separated from large spindle errors to nanometric level, thus confirming the effectiveness of the instrument based on the mixed method.

2.2 Precision nanometrology of flatness of large silicon wafer

Inspection of silicon wafer flatness is important for the manufacture of both wafer substrates and IC devices. The wafer is required to be not only locally flat over the die site for the IC production process, but also globally flat over the entire wafer for the chemo-mechanical planarization process. On the other hand, the transition from 200 mm diameter wafers to 300 mm diameter wafers is being performed, and precision nanomeasuring instruments are needed for flatness measurement of such large wafers.

Fig. 6 shows the schematic of a scanning multi-probe instrument with a slope measurement-based precision nanometrology technique [17,18]. Fig. 8 shows a photograph. There are two two-dimensional (2D) slope probes with a probe distance of D in the

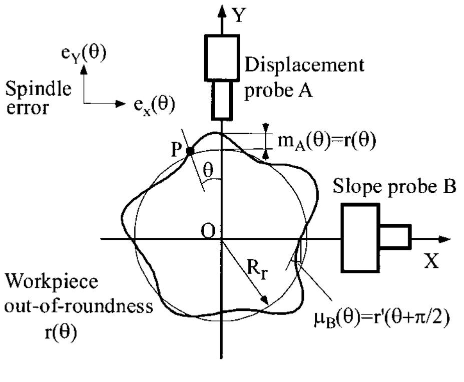

Fig. 2 Schematic of the mixed method

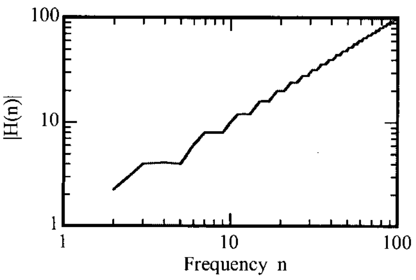

Fig. 3 Harmonic sensitivity of the mixed method

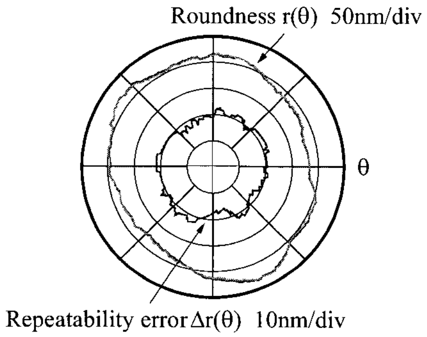

Fig. 4 Measured roundness error with the mixed method

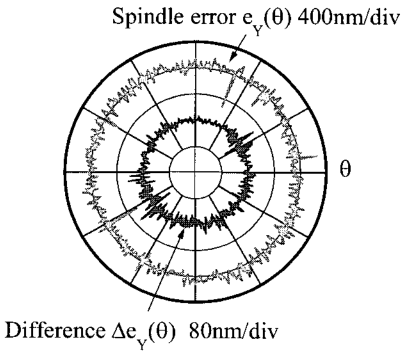

Fig. 5 Measured spindle error with the mixed method

sensor unit. The scanning in X-direction starts from the center of the wafer. At each sampling position x_i (i=1, 2,... M), the 2D surface local slopes at the points along two concentric circles are detected by the two angle probes simultaneously. The sampling positions along the circle are numbered as θ_j (j=1, 2,..., N). The Y-directional outputs $\mu_{1y}(x_i, \theta_j)$, $\mu_{2y}(x_i, \theta_j)$ of the angle probes at x_i, which correspond to the tilts about X-axis, can be expressed as:

$$\mu_{1y}(x_i,\theta_j)=f_y'(x_i,\theta_j)+e_{CX}(x_i)+e_{SX}(x_i,\theta_j) \tag{5}$$

$$\mu_{2y}(x_i,\theta_j)=f_y'(x_{i+1},\theta_j)+e_{CX}(x_i)+e_{SX}(x_i,\theta_j) \tag{6}$$

$$i=1, 2,\ldots, M-1, j=1, 2, \ldots, N$$

where, $e_{CX}(x_i)$ is the roll error of the sensor carriage, $e_{SX}(x_i, \theta_j)$ is the angular motion component of the wafer spindle about X-axis. $f'_y(x, \theta)$ is the Y-directional local slope of the wafer surface.

Similarly, the X-directional outputs $\mu_{1x}(x_i, \theta_j)$, $\mu_{2x}(x_i, \theta_j)$ of the angle probes can be expressed by

$$\mu_{1x}(x_i,\theta_j)=f_x'(x_i,\theta_j)+e_{CY}(x_i)+e_{SY}(x_i,\theta_j) \tag{7}$$

$$\mu_{2x}(x_i,\theta_j)=f_x'(x_{i+1},\theta_j)+e_{CY}(x_i)+e_{SY}(x_i,\theta_j) \tag{8}$$

where, $e_{CY}(x_i)$ is the yaw error of the sensor carriage, $e_{SY}(x_i, \theta_j)$ is the angular motion component of the wafer spindle about Y-axis. $f'_x(x, \theta)$ is the X-directional local slope of the wafer surface.

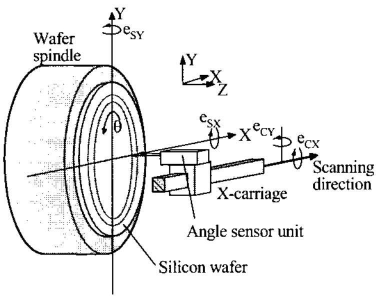

Fig. 6 A precision nanomeasuring instrument for flatness measurement of large silicon wafers

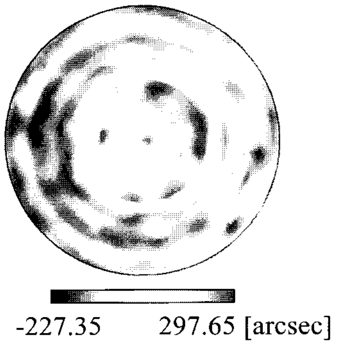

Fig. 7 A measured result of surface local slope map

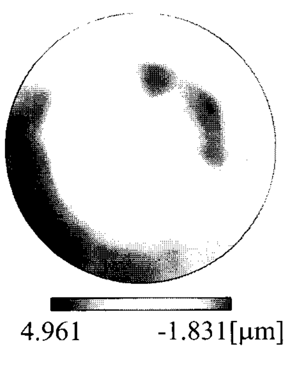

Fig. 8 A measured result of flatness

The surface local slopes and the error motions of the spindle and carriage can be separated from each other using Eqs. (5)-(8). The slope sensors have advantages of high resolution and large working distance, which are important for high-accuracy and high-speed measurement [19].

Fig. 7 shows a measured local slope map of the surface, and Fig. 8 shows the measured flatness obtained from the surface slope information.

2.3 Precision nanometrology of cylinder straightness

Cylinders are one of the most used precision parts in precision industries and measurement of the cylinder straightness is always an important task. Fig. 9 shows a schematic of a measuring instrument for precision nanometrology of cylinder straightness [20]. The system consists of two probe-units, each having three displacement probes. The two probe-units, which are placed on the two sides of the test cylinder, are moved by a scanning stage to scan the two opposed straightness profiles of the cylinder simultaneously. As can be seen in Fig. 10, the cylinder is scanned twice before and after rotating the cylinder 180 degrees about the X-axis. The probe outputs of the two scans can be expressed as:

1st Scan before180 degree rotation of the cylinder:

$$\begin{aligned}
m_1(x_i) &= f(x_i-d,0°)+e_Z(x_i)-de_{yaw}(x_i)+e_{m1}\\
m_2(x_i) &= f(x_i,0°)+e_Z(x_i)+e_{m2}\\
m_3(x_i) &= f(x_i+d,0°)+e_Z(x_i)+de_{yaw}(x_i)+e_{m3}\\
n_1(x_i) &= f(x_i-d,180°)-e_Z(x_i)+de_{yaw}(x_i)+e_{n1}\\
n_2(x_i) &= f(x_i,180°)-e_Z(x_i)+e_{n2}\\
n_3(x_i) &= f(x_i+d,180°)-e_Z(x_i)-de_{yaw}(x_i)+e_{n3}\\
& i=1, 2, \ldots, N
\end{aligned} \tag{9}$$

2nd Scan after 180 degree rotation of the cylinder:

$$\begin{aligned}
m_{1r}(x_i) &= f(x_i-d,180°)+e_{Zr}(x_i)-de_{yawr}(x_i)+e_{m1}\\
m_{2r}(x_i) &= f(x_i,180°)+e_{Zr}(x_i)+e_{m2}\\
m_{2r}(x_i) &= f(x_i,180°)+e_{Zr}(x_i)+e_{m2}\\
m_{3r}(x_i) &= f(x_i+d,180°)+e_{Zr}(x_i)+de_{yawr}(x_i)+e_{m3}\\
n_{1r}(x_i) &= f(x_i-d,0°)-e_{Zr}(x_i)+de_{yawr}(x_i)+e_{n1}\\
n_{2r}(x_i) &= f(x_i,0°)-e_{Zr}(x_i)+e_{n2}\\
n_{3r}(x_i) &= f(x_i+d,0°)-e_{Zr}(x_i)-de_{yawr}(x_i)+e_{n3}\\
& i=1, 2, \ldots, N
\end{aligned} \tag{10}$$

where $f(x_i)$ is the straightness profile, d is the probe interval, N is the sampling number over the entire scanning length, $e_Z(x_i)$ and $e_{yaw}(x_i)$ are the Z-directional translation error and yaw error of the scanning stage, respectively. e_{mj}, e_{nj} (j=1, 2, 3) are the unknown zero-values of the probes in the probe-units.

The motion errors of the scanning stage as well as the zero-values of the probes can be removed using the probe outputs shown in Eqs. (9) and (10).

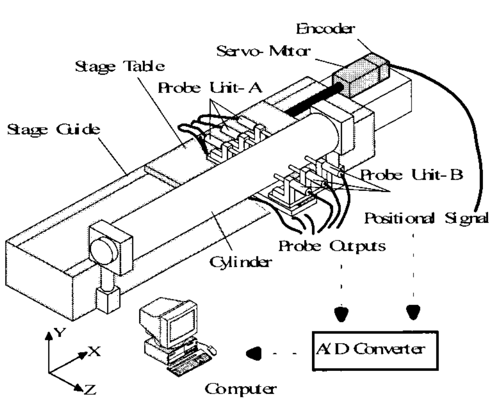

Fig. 9 Schematic of a precision nanomeasuring instrument of cylinder straightness

Fig. 11 shows a measurement result by the instrument. The repeatability was on the order of 100 nm over a measurement length of 600 mm. The α in the figure is a combination of the zero-values of the probes called the zero-adjustment error. The value of the zero-adjustment error, which is identified as the biggest error source, was accurately compensated for in the developed instrument.

3. Precision nanometrology in a precision nanomachining instrument

The critical depth of brittle-to-ductile transition for brittle materials is on the order of tens to hundreds of nanometers. Interest in the ductile-regime machining of brittle materials has brought about great efforts to study the nanocutting mechanism. Fig. 12 shows a precision nanomachining instrument, which is suitable for nanocutting experiments of brittle materials[21-24]. This instrument is basically a two-dimensional planar. The orthogonal geometry enables the measurement of cutting and thrust forces with a specific depth of cut.

A couple of precision nanometrology techniques have been developed for assuring the successful nanomachining experiments. A technique shown in Fig. 13 has also been constructed to make it easy to locate and image the very small machined area. Fig. 14 shows the imaged nanoindent with a 3nm depth made by the instrument (5mm conical indenter on (100) single crystal silicon). The machining motions in both infeed and crossfeed directions can be controlled to nanometer level. Figs 15 shows successful nanoscratching results. The tool-sample contact and tool tilt adjustment can also be made to nanometer accuracy.

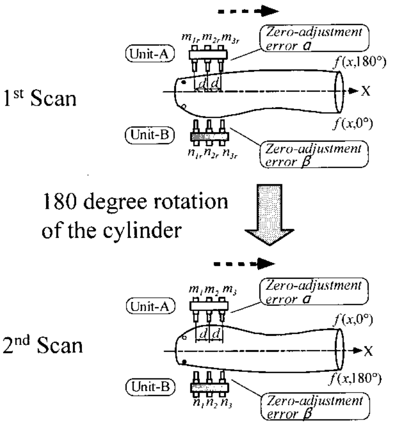

Fig. 10 Repeated scans

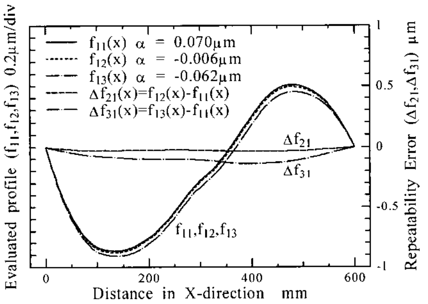

Fig. 11 Measurement results of cylinder straightness

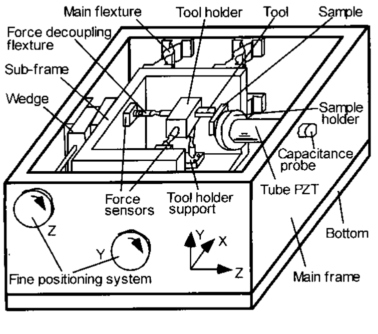

Fig. 12 A precision nanomachining instrument

4. Precision nanometrology in a precision nanofabrication system for large area microstructured surfaces

Nanofabrication of precision 3D microstructured surfaces over large areas are important for optical and metrological purposes. In the wavelength range of tens of micrometers to hundreds of micrometers, diamond turning with fast tool servo (FTS)[25-27] is superior to the electronic method and the optical method.

Fig. 16 shows a precision nanofabrication system based on diamond turning with FTS[28,29]. Fabrication of a sinusoidal grid surface, which is used as the measurement reference of a surface encoder for multi-axis position measurement, has been conducted. The profile of the grid surface is a superposition of sinusoidal waves in the X-direction and the Y-direction with spatial wavelengths of 100 μm and amplitudes of 100 nm over a large area of 150 mm in diameter. A couple of precision nanometrology techniques have been developed for improvement of the fabrication accuracy. Positioning of the tool tip to the spindle axis center (center-alignment) has been accomplished to sub-micrometer level

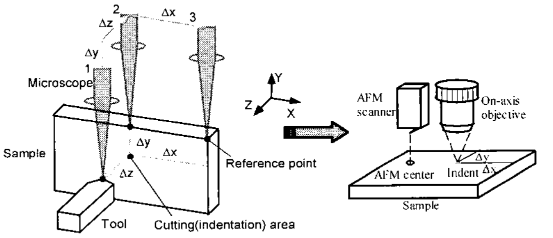

Fig. 13 Locating and imaging the nanomachining point

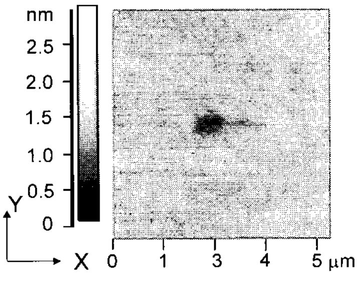

Fig. 14 A located and imaged "nanoindent" (3nm depth)

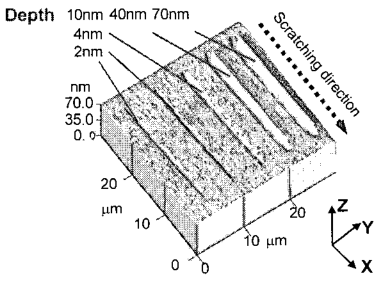

Fig. 15 Results of "nanoscratching"

with the aid of an AFM and an interference microscope, resulting in a great reduction of the distortion of grid surface profile caused by the center-alignment error. An efficient evaluation technique based on two-dimensional DFT of the interference microscope image of the sinusoidal grid surface has also been developed for the fabricated surfaces (Fig. 17). The error-component caused by the round nose geometry of the diamond tool has been identified by the evaluation technique. The amplitude of the error-component has been reduced to 1.4 nm through a compensation procedure based on the evaluation result. The flatness of the entire surface has also been improved to 0.14 μm through precision nanometrology of the error motions of the diamond turning machine (Fig. 18). Consequently the sinusoidal waves have been successfully fabricated on the entire grid surface with a diameter of 150 mm (Fig. 19).

5. Precision nanometrology in a nanomechtronics system for planar motion control

Precision planar motion (XY and/or XYθ_Z) stages are widely used in semiconductor manufacturing systems, precision machine tools, and scanning probe measurement systems. These stages are required to have sub-micron to nanometer positioning resolution and/or accuracy as well as characteristics such as high speed, long travel range, and compact size.

Fig. 20 shows the schematic of a surface motor-driven XY planar motion stage cored with a precision nanometrology technique called surface encoder [30,31] (Fig. 21) for XYθ_Z position measurement [32)33)]. The surface motor consists of four linear motors placed on the same surface, two pairs in the XY-axes. The magnetic array and the stator winding of the linear motor are mounted on the platen (the moving element) and the stage base, respectively. The platen can be moved in the X-direction by the X-linear motors, and in the Y-direction by the Y-linear motors. It can also be rotated about the Z-axis if the X- or Y-linear motors generate a moment about the Z-axis. The surface encoder consists of two two-

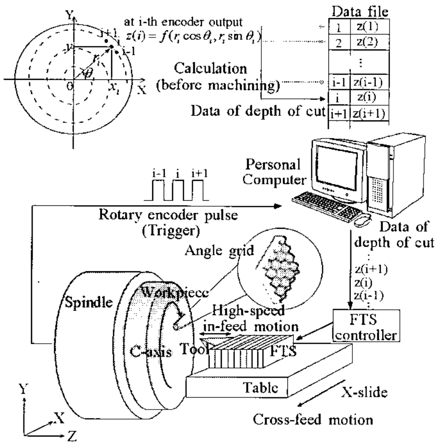

Fig. 16 A precision nanofabrication system for generation of large area microstructured surface

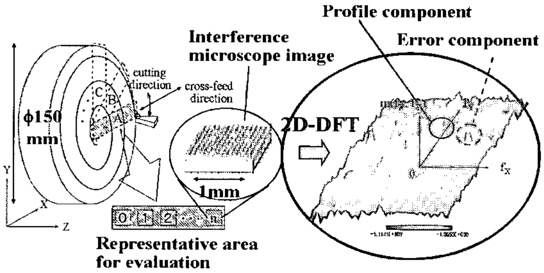

Fig. 17 A precision nanometrology technique for evaluation of the fabricated microstructured surface

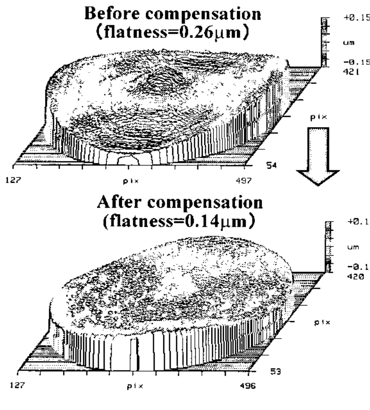

Fig.18 Flatness improvement by precision nanometrology

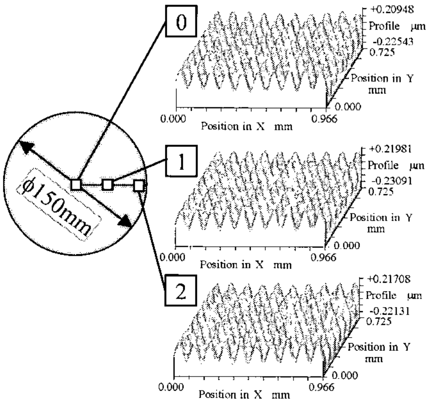

Fig.19 Results of precision nanofabrication

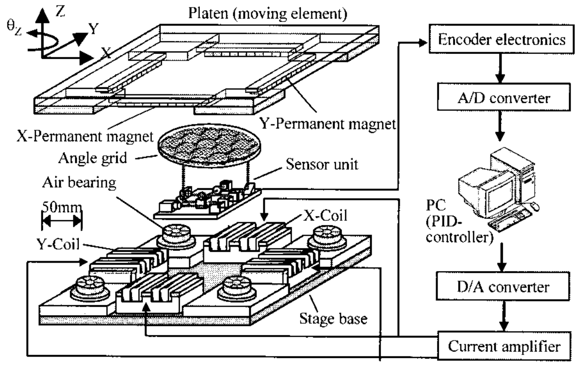

Fig.20 A precision a planar motion stage

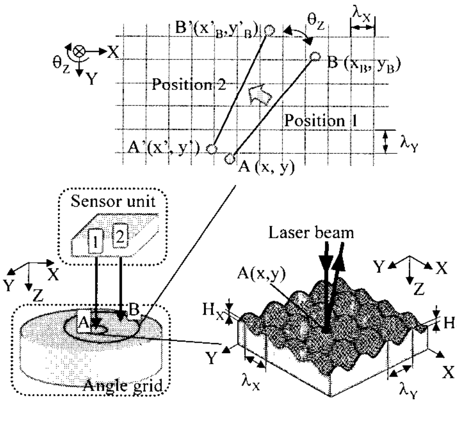

Fig.21 The surface encoder for precision nanometrology of multi-axis positions

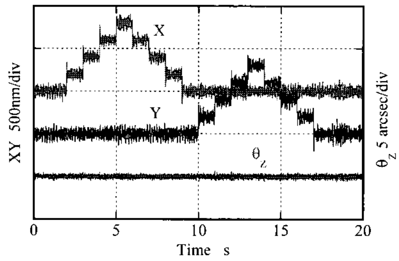

Fig.22 A result of multi-axis positioning

dimensional angle sensors and an angle grid with two-dimensional sinusoidal waves on its surface. The angle grid is mounted on the platen of the stage which is levitated by air-bearings. The angle sensors and the air-bearing pads are fixed on the stage base so that the motion of the platen is not affected by the electronic cables and air hoses. The XY-positions and θ_Z rotation of the platen can be obtained from the angle sensor outputs with resolutions of approximately 10 nm and 0.1 arc-seconds, respectively. The surface encoder is placed inside the stage so that the stage system is very compact in size. As can be seen in Fig. 22, precision positioning can be carried out independently in X, Y and θ_Z with resolutions of 100 nm and 1 arc-second, respectively.

6. Conclusions

A new field of metrology called precision nanometrology has been presented. A couple of precision nanosystems cored with precision nanometrology technologies have been demonstrated. For the sake of page number limitation, only examples the author has been involved in are shown in this paper. It should be pointed out that a lot of technologies have been developed by researchers in this field.

The precision nanometrology is expected to play increasingly important roles in precision industries and nanoengineering. It is necessary to continuously make great efforts in developing new precision nanometrology technologies and extending its applications.

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