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Development of a novel multifunctional Abbé-free 12"-wafer measuring stage for semiconductor manufacturing

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To design and develop a novel multifunctional Abbé free 12" wafer measuring stage is presented in this paper. The developed stage is designed and optimized, to be capable of integrating various optical measuring functional modules for defect detection and classification, CD measurement, 3-D dimensional inspection, and surface spectrum measurement in automated optical test (AOI). In work, the Abbé-principle design is adopted to minimize the volumetric errors of the stage's motion. With the framework of the stage established, the automatic parametric design is implemented with finite element method software to determine the lightest weight design within the tolerance of deformation and modal of the system. Ultra-low thermal-expansion material (Ohara CCZ-HS) is used to form a novel three-dimensional coordinate reference datum module located in the center of the stage to establish a precise metrological coordinate system for the stage. Furthermore, three-axis laser interferometry is designed to measure and compensate the Abbé-free point of the working datum, in order to maximize its positioning accuracy. By doing so, the volumetric errors induced by the stage movement can be minimized, so the positioning accuracy of the three-axis stage can be significantly improved. This system can achieve a scanning speed of 100 mm/s, and within the 300 × 300 × 5 mm measuring range, the absolute spatial positioning error is less than 50 nm, which can satisfy most stop-and-scan metrological operations in semiconductor manufacturing processes.

1. Introduction

With the fast development of the semiconductor industry, the wafer's critical dimension has already reached the nanoscale level. The size of the wafer becomes larger when its lithography patterns are significantly reduced down a nanometer scale. Therefore, the need to measure the nanoscale dimensions in large areas is highly demanded. This research aims to optimize a wafer measuring stage developed in the precision metrology lab at the National Taiwan University [1] as the second generation platform. The purpose of the development is to provide precise and stable positioning within a 300 × 300 × 5 mm working volume, which is sufficient for the 12" wafer, by inducing the parametric design to upgrade the structure of the wafer stage. And this improvement also makes this wafer stage compatible with various measuring probes, which can perform AOI testing, and other types of semiconductors measurement.

2. Working principle of the wafer measuring stage

The wafer measuring stage developed in the precision metrology lab at the national Taiwan university is shown in **Error! Reference source not found.**, and the CAD design is shown in **Error! Reference source not found.**.

Fig. 1 Wafer measuring stage in the precision metrology lab at national Taiwan university.

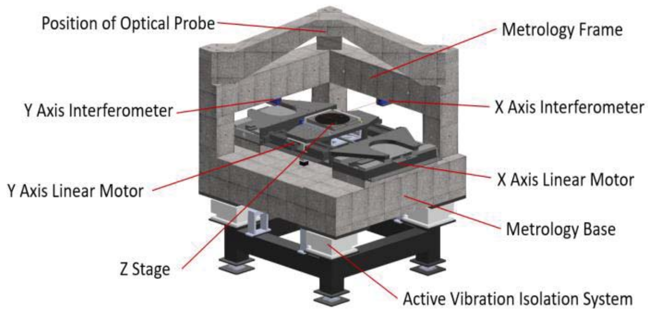


Fig. 2 3D CAD design of wafer measuring stage

The optical measurement probe is designed to be rigidly mounted on the center of the arch of the metrology frame and is perfectly stationary during the measurement process. The linear motors installed on the base provide the positioning and scanning ability of the wafer measuring stage in 3 axes.

The base and the frame of this stage are made of granite to reduce vibration in a passive manner. In addition, four active vibration isolation systems are installed on each corner of the stage to reduce the vibration further.

Z stage of the wafer measuring stage is integrated with the wafer chuck and is made of nanoporous materials to provide wafer holding. When the negative pressure is supplied, it can suck the wafer during measurement. And three reference mirrors on the Z stage act as a stable and precise datum coordinate of this wafer stage. These reference mirrors are for interferometers that provide the position information for servo control of the wafer stage. More detail is described in the next section.

3. Design of the wafer measuring stage

The principle of designing the nanopositioning system is introduced in the article [2]. Here, we summarize the principle in the article and propose the design flowing points. First, the stage should follow the Abbé principle. That means the moving and measuring axes should be on the same axis. This way, the unavoidable volumetric error caused by the unparallel moving and measuring axis can be eliminated. Second, to keep the stage as stable as possible during the measurement process. The deformation of the structure should be minimized. And, any undesired harmonic motion should be avoided during the measuring process, so the natural frequency of the frame should be as high as possible. Third, to eliminate the Abbé error instead of using an optical encoder inside the linear motor as the feedback device. We utilize the laser interferometer to trace the movement of the measurement point of the optical probes to realize the 3D Abbé-free design.

3.1 Design that satisfies the Abbé principle

Several designs that satisfy the Abbé principle[3] have been implemented in other articles. The TriNano[4] system developed at Eindhoven University of Technology designed a special stage with a tetrahedron shape and made 3 moving axes intersect on the measurement point to eliminate the Abbé error. Another design is the LuphoScan[5] precision measuring machine owned by Taylor Hobson. The machine comprises two translational axes and two rotating axes. This design ensures the probe is orthogonal to the inspection surface, and the two translation axes can precisely intersect at the center point of the probe by using a real-time positioning compensator. In this setting, the design can satisfy the generalized Abbé's theorem in three dimensions and theoretically achieve zero Abbé error. Other designs like NPMM-200[6] from Ilmenau University and Isara 400[7] developed by IBS Precision Engineering utilize interferometers on each axis and directly trace the movement of the point of measurement.

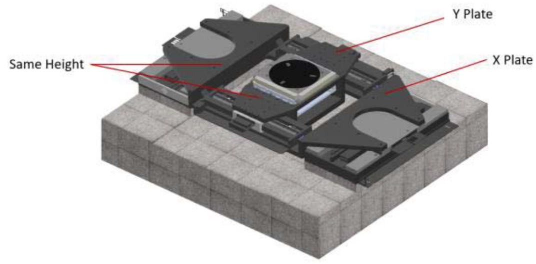


Fig. 3 Co-planar design of the wafer measuring stage

In our system, we implement the box-in-box design to make the Y plate inside the X plate, as shown in Fig. 3. The height of these two axes is at the same level. This setup is also called the co-planar structure and is commonly present in the nanoscale precision machine [8, 9]. Compared to stacking up the stage, this design can minimize the Abbé error in the Z direction.

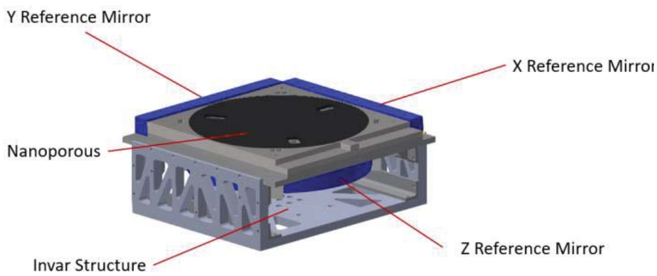


Fig. 4 3D CAD design of the Z stage as the system's reference metrological datum.

A specially designed Z stage and laser interferometer system is utilized to eliminate the Abbé error in the X and Y direction. The Z stage in Fig. 4 consists of three reference mirrors acting as the system's reference datum coordinate.

We assemble the mirror and stage with specially selected optical glue to permanently fix them together. The advantage of using the adhesive method is that the optical glue has a nearly similar thermal expansion coefficient to the reference mirror. So the thermal stress between the structure can be minimized. Furthermore, the glue can provide sufficient flexibility to prevent the mirror from breaking under introducing vibrations.

Orthogonality between mirrors is adjusted by a highly accurate coordinate measuring machine (CMM) and Hexapod, shown in Fig. 5, before permanently gluing the mirror with the Z stage. The reference mirror is first fixed on the Hexapod, and we check the position and orientation of the mirror with CMM. According to the result, we adjust the mirror's orientation with Hexapod. After a few iterations, we can put the glue between the mirror and the Z stage. The orthogonality between mirrors can achieve to be less than 5 arcseconds by this method.

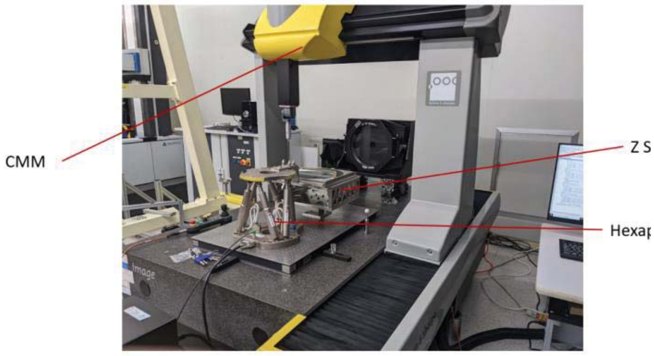


Fig. 5 Assembling process of attaching the reference mirror with CMM and Hexapod

The precisely assembled Z stage provides a datum coordinate for the wafer measuring stage; therefore, the measurement spots of the interferometer are set to be on the reference mirrors. And the extension of these laser lines intersects at the measuring point of the optical probe, which is usually at the center point of the top surface of the wafer. The volumetric Abbé error can be eliminated on all 3 axes by directly measuring this point.

3.2 Layout of the interferometer

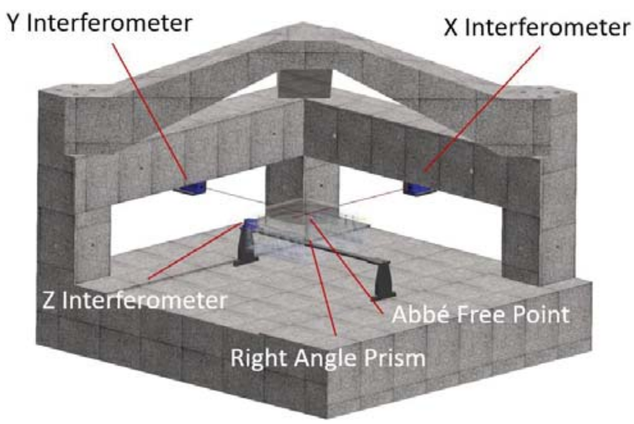


Fig. 6 layout of the interferometers

There are 3 interferometers in the wafer measuring stage, one for each axis shown in Fig. 6. Providing the positioning feedback information. The interferometer of the X and Y axis is directly fixed below the metrology frame. The laser line is calibrated to be orthogonal with the reference mirror and passes through the measuring point of the optical probe. This alignment is extremely crucial to achieve the Abbé free design since the alignment makes the X and Y interferometers intersect on the measurement point, also known as Abbé free point. We cannot directly align the interferometer with the Z mirror by considering avoiding the constrain of the space, so we designed a bridge structure passing through the Z stage. The interferometer is fixed on one end of the bridge, and a right-angle prism is placed right below the Abbé free point, which makes the laser beam bend 90 degrees upward. So, the three interferometers' laser line intersects right at Abbé free point.

3.3 Parametric design and structural analysis of wafer measuring stage

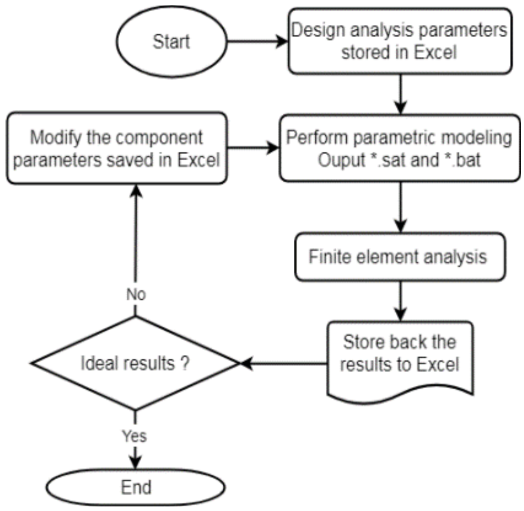
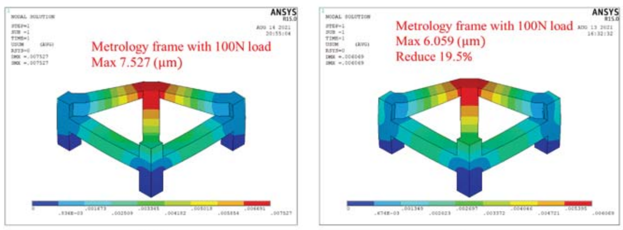


Fig. 7 Flowchart of parametric design

To reduce the measurement error, the structure of the wafer measuring stage should be as stiff as possible, especially the metrology frame hanging the optical probe and fixing the interferometer and the hall Z stage that act as the datum reference coordinate of the system.



(a) (b)

Fig. 8 (a) Deformation analysis of metrology frame with initial parameters (b) Deformation analysis of metrology frame with improved parameters determined by parametric design

Table 1 Mode frequency comparison of the frame with initial and improved parameters

Mode	1	2	3	4	5	6
Initial parameters (Hz)	66	150	196	230	267	289
Improved parameters (Hz)	74	163	224	259	283	303
Improvement (%)	11.6	8.7	13.8	12.4	5.9	4.9

Therefore, we induce the parametric design[10] with finite element method (FEM) software to improve the strength of the structure in the design phase. Fig. 7 shows the flowchart of the parametric design. Structures' framework is established first, but some dimensions are chosen as the parameters that can be modified during the improvement process.

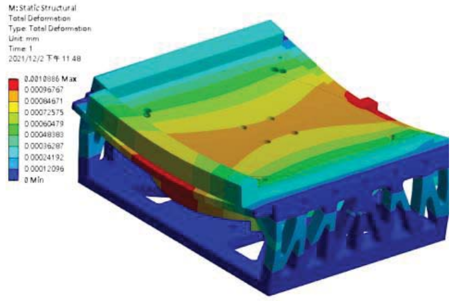


Fig. 9 Deformation analysis of Z stage with improved parameters

Table 2 Mode frequency analysis of Z stage with improved parameters

Mode	1	2	3	4	5	6
Frequency (Hz)	327	528	686	751	1041	1073

With initial dimensions, the deformation and the mode frequency are calculated by FEM software iteratively [11]. These results are saved in an Excel spreadsheet. The data in the spreadsheet can determine the parameters of the next iteration's model. And the Python code is used to integrate these processes and implement the gradient descent optimization algorithm during the iterations.

The objective function of the gradient descent algorithm is the structure's weight. Two constraints are considered. First, the deformation should less than the acceptable value. The second is that the mode frequency should be higher than the setting value. After a few iterations, we can determine and obtain the lightest design with the acceptable deformation and high enough mode frequency. Fig. 8 compares the initial design and shows the improved result. From the picture, the deformation of the initial dimension is not in the tolerance, With the improvement, the deformation can be effectively reduced, and the mode frequency becomes higher than the initial dimension. The mode frequency result is shown in Table 1. And the deformation analysis of the Z stage is shown in Fig. 9 with the maxima deformation to be less than 1 µm. The mode frequency is also listed in Table 2

The actual modal testing with impact hammer and accelerometer is performed as well. Results of the FEM simulation and measurement are compared in Table 3. It shows that the error between the simulation and measuring is within 8%.

Table 3 Comparison of mode frequency of the wafer measuring stage with the FEM Simulated and measured data from an accelerometer

Mode	1	2	3	4	5	6
Simulation (Hz)	145	150	206	261	370	397
Measurement (Hz)	135	160	215	283	373	409
Error (%)	7.57	-5.86	-3.84	-7.65	-0.73	-2.78

In addition, it is worth to mention the structures of the Z stage are made of invar, and the reference mirror is made of CCZ-HZ. Both are ultra-low thermal expansion materials. Using ultra-low thermal expansion materials can further increase the stability of the wafer measuring stage with temperature fluctuation.

4. Conclusions

In this paper, we design a wafer measuring stage that satisfies the 3D Abbé principle achieved by implementing the co-planar structure and utilizing a laser interferometer to monitor and control the three-axis positions of the specially designed Z stage which acts as a three-dimensional coordinate reference datum module. And at the design phase, the parametric design is induced to find the dimensions that make the part lightest but still satisfy the deformation and mode frequency requirement. The modal measurement is also implemented to compare with the simulation. The result shows that the measurement and simulation error is less than 8%. The accuracy of the nano-measuring platform will be further measured and evaluated in the next stage of the development.

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