

MARKER HAVING FOCUSING AND TILT-CORRECTION DESIGN AND ALIGNMENT METHOD

TECHNICAL FIELD

The present invention relates to a mark with a focusing and tilt-correction design as well as an alignment method and, more particularly, to a mark comprising an alignment sub-mark and at least one pair of focusing sub-marks as well as an alignment method thereof.

BACKGROUND

An integrated circuit (IC) fabrication process typically involves multiple photolithographic steps. Except for the photolithographic step for the first layer, exposure in each subsequent photolithographic step is preceded by precise positioning of a pattern of the layer to be processed in relation to a previously formed pattern (i.e., mark), in order to ensure correct relative placements between the patterns in different layers, i.e., accurate overlays.

In the prior art, alignment systems based on optical imaging, such as Nikon FIA and Ultratech MVS, are ones of those commonly used in photolithography tools. FIA systems employ simple marks, as exemplified in Fig. 1, while Ultratec MVS systems are capable of mark learning and use non-predefined marks. In addition, US6344698 B2 and CN102103336 both provide marks that are less affected by their fabrication processes by taking into account the impact thereof.

In fact, besides fabrication process, there are many other factors that may also affect measurement accuracy.

First of all, distortion is a common type of aberration which has a considerable impact on the measurement reproducibility of an optical imaging system due to its

nonlinear coupling with the uncertainty in the position of the mark in the field of view (FoV). Though this can be mitigated by an FIA system through performing multiple iterations to make the mark always stay at a fixed position during the measurement, the iterations are significantly time-consuming.

Additionally, the measurement reproducibility may also be affected by defocusing or tilting of the mark, and as shown in Fig. 2, an angle of tilt α can lead to an error D . Although focusing and leveling systems employed in photolithography tools are capable of tilt-and-defocus correction, as the measurement planes of these systems lie on the top surface of photoresist, and since the alignment mark is located on the bottom surface of the photoresist in some scenarios, they cannot provide high-precision focusing and leveling in such cases due to fluctuations in photoresist thickness.

Furthermore, although autofocus techniques have been widely used in alignment sensors in optical imaging systems, there has not been invented as yet any sensor that is capable of both auto focusing and tilt correction.

SUMMARY OF THE INVENTION

It is an object of the present invention to provide a mark with a focusing and tilt-correction design and an alignment method. The mark includes an alignment sub-mark and at least one pair of focusing sub-marks configured to eliminate the impact of tilt of the mark and reduce the impact of distortion thereon while achieving focusing.

To this end, there is provided in the present invention a mark with a focusing and tilt-correction design, which comprises:

an alignment sub-mark and at least one pair of focusing sub-marks, the alignment sub-mark being centered on any one of the line segments interconnecting

the respective at least one pair of focusing sub-marks, wherein focusing and leveling of the alignment sub-mark is enabled by determining positions of optimal focal planes for the at least one pair of focusing sub-marks.

Additionally, the alignment sub-mark may assume the shape of a plain cross, a plain cross superimposed with a diagonal cross, horizontal bars or vertical bars.

Additionally, the alignment sub-mark may be centered at the midpoint of any one of the line segments interconnecting the respective at least one pair of focusing sub-marks.

Additionally, the alignment sub-mark may have a width that is greater than the size of discretized particles.

Additionally, the width of the alignment sub-mark may be greater than two times a Point Spread Function (PSF) width.

Additionally, the focusing sub-marks may resemble squares or gratings.

Additionally, the gratings may be horizontal or vertical ratings.

Additionally, the at least one pair of focusing sub-marks comprise a pair of square focusing sub-marks, a pair of horizontal-grating-like focusing sub-marks and a pair of vertical-grating-like focusing sub-marks.

The present invention also proposes an alignment method for use with the mark as defined above. The alignment method comprises the steps of:

providing on a workpiece n sets of marks each having a focusing and tilt-correction design and comprising an alignment sub-mark and at least one pair of focusing sub-marks, wherein the alignment sub-mark is centered on any one of the line segments interconnecting the respective at least one pair of focusing sub-marks;

performing an initial alignment on each set of marks by an alignment system;

vertically stepping a workpiece table by a predetermined distance and, for each set of marks, obtaining optimal focal plane positions $\{P_i, Q_i\}$ for the at least one pair

of focusing sub-marks using their focal plane determination criterion values and an optimal focal plane determination method, wherein P_i and Q_i represent the optimal focal plane positions of one pair of focusing sub-marks in an i -th set of marks, where $i=1, 2, \dots, n$ and $n \geq 3$;

for each set of marks, obtaining an initial optimal focal plane position value M_i of the alignment sub-mark, as well as an initial tilt value T_i thereof based on the optimal focal plane positions $\{P_i, Q_i\}$ for the at least one pair of focusing sub-marks as well as on a horizontal distance $Dis(P_i, Q_i)$ corresponding to the set of marks, wherein

$$M_i = \frac{P_i + Q_i}{2}, \text{ and } T_i = \arctan\left(\frac{P_i - Q_i}{Dis(P_i, Q_i)}\right);$$

determining the position M and tilt T of an optimal focal plane for the work piece using mean filtering or median filtering method based on the initial optimal focal plane position values M_i and initial tilt values T_i of the alignment sub-marks; and

moving the workpiece table vertically based on the position M and tilt T of the optimal focal plane for the workpiece so as to compensate for the vertical positions of the alignment sub-marks.

Additionally, the focal plane determination criterion may comprise a gradient amplitude and a PSF width.

Additionally, the focusing sub-marks may resemble squares or gratings.

Additionally, the focal plane determination criterion for each focusing sub-mark resembling a grating may be a gradient amplitude of an image of the sub-mark.

Additionally, the focal plane determination criterion for each focusing sub-mark resembling a square may be a PSF width of an image of the sub-mark. Specifically, a gray distribution can be established from gray values sampled from

one or more elongate portions of the square and used to derive an h value, based upon which the focal plane position can be determined.

Additionally, obtaining the optimal focal plane positions $\{P_i, Q_i\}$ for the at least one pair of focusing sub-marks in each set of marks may comprise:

stepping the workpiece table by a predetermined distance;

capturing an image of the workpiece table after each stepping in a vertical direction;

calculating focal plane determination criterion values from the captured images;

and

determining the optimal focal plane positions from a fitted curve.

Additionally, obtaining the optimal focal plane positions $\{P_i, Q_i\}$ for the at least one pair of focusing sub-marks in each set of marks may comprise:

calibrating and establishing a relationship between focal plane determination criterion values and vertical positions of the workpiece table;

capturing an image of the workpiece table at its current vertical position;

calculating a focal plane determination criterion value from the captured image;

obtaining the distance d from the current vertical position of the workpiece table from a focal plane based on the established relationship between focal plane determination criterion values and vertical positions of the workpiece table as well as on the calculated focal plane determination criterion value;

vertically moving the workpiece table by distances of d and $-d$ from its current vertical position and capturing images of the workpiece table at the respective new positions, based on which focal plane determination criterion values V_1 and V_2 are calculated; and

determining the optimal focal plane positions for the at least one pair of focusing sub-marks by comparing V_1 with V_2 .

Compare to the prior art, the mark with a focusing and tilt-correction design and the alignment method according to the present invention enable high-precision focusing and leveling of the alignment sub-mark. On the one hand, measurement reproducibility is improved by eliminating the impact of tilt on the mark while achieving focusing. On the other hand, constraints for mark width are derived from an analysis of how distortion impacts measurement reproducibility, resulting in a further improvement in measurement reproducibility.

BRIEF DESCRIPTION OF THE DRAWINGS

Fig.1 is a schematic illustration of an FIA mark.

Fig. 2 schematically illustrates the effect of defocusing or tilting.

Fig. 3 is a schematic illustration of a mark according to a first embodiment of the present invention.

Fig. 4 schematically illustrates how grey values are sampled in accordance with the first embodiment of the present invention.

Fig. 5 schematically illustrates a gray distribution established from the grey values sampled in accordance with the first embodiment of the present invention.

Fig. 6 schematically illustrates a positional relationship between an alignment sub-mark and focusing sub-marks according to the first embodiment of the present invention.

Fig. 7 diagrammatically shows the vertical position and tilt M_i , T_i of each alignment sub-mark derived from calculated vertical positions P_i , Q_i of corresponding focusing sub-marks.

Fig. 8 diagrammatically shows how the position of a workpiece (wafer) is calculated from the positions X , Y of several alignment sub-marks.

Fig. 9 diagrammatically shows how distortion impacts measurement

reproducibility.

Fig. 10 is a schematic illustration of a mark according to a second embodiment of the present invention.

Fig. 11 is a schematic illustration of a mark according to a third embodiment of the present invention.

In the figures: α denotes a tilt of a test object; D , an error; 10, a square focusing sub-mark; 30, a square focusing sub-mark; 11, a horizontal-grating-like focusing sub-mark; 31, a vertical-grating-like focusing sub-mark; 12, a vertical-grating-like focusing sub-mark; 32, a vertical-grating-like focusing sub-mark; 20, an alignment sub-mark; h , an PSF width; 1, an optimal focal plane for a focusing sub-mark on one side; 2, an optimal focal plane for an alignment sub-mark; and 3, an optimal focal plane for a focusing sub-mark on the other side.

DETAILED DESCRIPTION

Several embodiments of the invention are described below and explained in further detail with reference to the accompanying drawings. Features and advantages of the invention will be more apparent from the following detailed description, as well as from the appended claims. Note that the accompanying drawings are provided in a very simplified form not necessarily presented to scale, with the only intention of facilitating convenience and clarity in explaining the embodiments.

EMBODIMENT 1

As shown in Fig. 3, in this embodiment of the present invention, there is provided a mark with a focusing and tilt-correction design, which comprises an alignment sub-mark 20, as well as at least one pair of focusing sub-marks each resembling a square or a grating. In the latter case, each of the focusing sub-marks may resemble a horizontal grating or a vertical grating. The at least one pair of

focusing sub-marks may include a pair of focusing sub-marks each resembling a square, a pair of focusing sub-marks each resembling a horizontal grating and a pair of focusing sub-marks each resembling a vertical grating. Specifically, in this Embodiment, the at least one pair of focusing sub-marks may include a square focusing sub-mark 10, a square focusing sub-mark 30, a horizontal-grating-like focusing sub-mark 11, a horizontal-grating-like focusing sub-mark 31, a vertical-grating-like focusing sub-mark 12 and a vertical-grating-like focusing sub-mark 32, wherein the square focusing sub-mark 10 and the square focusing sub-mark 30 are a pair of focusing sub-marks each resembling a square, the horizontal-grating-like focusing sub-mark 11 and the horizontal-grating-like focusing sub-mark 31 are a pair of focusing sub-marks each resembling a grating, and the vertical-grating-like focusing sub-mark 12 and the vertical-grating-like focusing sub-mark 32 are also a pair of focusing sub-marks each resembling a grating. The alignment sub-mark 20 may be a cross-shaped mark or a mark assuming the shape of a plain cross superimposed with a diagonal cross and is used for alignment. In this Embodiment, the alignment sub-mark 20 is a cross-shaped mark that comprises a horizontal bar and a vertical bar crossing the horizontal bar at right angles and is centered at the midpoint of any of the line segments interconnecting the respective pairs of focusing sub-marks, so that the two focusing sub-marks in any pair are symmetric to each other with respect to the alignment sub-mark. As such, the height and tilt of the alignment sub-mark 20 can be calculated based on the heights of the focusing sub-marks on both sides relative to the alignment system as well as on a positional relationship between the alignment sub-mark and the two focusing sub-marks on both sides. This enables high-precision focusing and leveling for the alignment sub-mark 20. Wherein, the alignment sub-mark 20 has a width that is greater than the size of discretized image particles. With the at least one pair of

focusing sub-marks, in addition to focal plane adjustment for the plane where the alignment sub-mark 20 is located, horizontality adjustment is also made possible during alignment. That is, high-precision focusing and leveling for the plane where the alignment sub-mark 20 is located is enabled with the at least one pair of focusing sub-marks prior to the measurement of the alignment sub-mark 20. Determination of an optimal focal plane for any focusing sub-mark requires selection of a focal plane determination criterion. There are two commonly-used focal plane determination criteria, i.e., gradient amplitude and PSF (Point Spread Function) width.

In this Embodiment, for each of the grating-like focusing sub-marks 11, 12, 31 and 32, a focal plane may be determined using its gradient amplitude obtained through convolving its image with Sobel operators and then summing the convolutions, i.e., according to the following formulae:

$$Dx = Image * SobelX$$

$$Dy = Image * SobelY$$

$$V = \sum_{image} \sqrt{Dx_i^2 + Dy_i^2}$$

where, *Image* represents the original image, *SobelX* and *SobelY* denote the horizontal and vertical Sobel operators, respectively, *Dx* and *Dy* represent images resulting from the horizontal and vertical edge detections, respectively, and *V* is a gradient approximation, i.e., the focal plane determination criterion.

In this Embodiment, for each of the square focusing sub-marks 10 and 30, a focal plane may be determined based on a PSF width *h*, as shown in Fig. 5, solved from the gray distribution shown in the same figure. The gray distribution can be established through summation (projection) of gray values sampled from one or more elongate portions of the square mark, as indicated by the dashed box in Fig. 4. The PSF width *h* can serve as the criterion for determining the focal plane. That is, the position of the focal plane can be determined based on the magnitude of the PSF

width h .

Subsequent to selection of the focal plane determination criterion, the optimal focal plane can be determined using either of the two methods as described below.

The first method includes the steps of:

- (1) stepping the workpiece table by a predetermined distance;
- (2) capturing an image of the workpiece table after each stepping in the vertical direction;
- (3) calculating focal plane determination criterion values from the captured images; and
- (4) determining the optimal focal plane position from a fitted curve.

The second method includes the steps of:

- (1) calibrating and establishing a relationship between focal plane determination criterion values and vertical positions of the workpiece table;
- (2) capturing an image of the workpiece table at its current vertical position;
- (3) calculating a focal plane determination criterion value from the captured image;
- (4) obtaining the distance d from the current vertical position of the workpiece table from the focal plane based on the relationship between focal plane determination criterion values and vertical positions of the workpiece table established in step (1) as well as the focal plane determination criterion value calculated in step (3);
- (5) vertically moving the workpiece table by distances of d and $-d$ from its current vertical position, capturing images of the workpiece table at the respective new positions, and calculating focal plane determination criterion values V_1 and V_2 ;
- (6) determining the optimal focal plane position by comparing V_1 with V_2 .

In step (1) of the second method, since the alignment system (including its

camera) generally remains quiescent, the vertical position of the workpiece table or that of the mark can be used to represent the vertical distance from the mark to the camera. Therefore, as used in the description of step (1), the term “vertical position of the workpiece table” may be interchangeable with “vertical position of the mark”, with the same effect being achieved. It is noted that since this Embodiment is described in the context where the system is implemented with the wafer being horizontally placed and the camera capturing images in the downward direction, the vertical position of the mark may refer either to the vertical position of the alignment sub-mark or to the vertical positions of the focusing sub-marks, which are at the same height.

In step (4) of the second method, with the relationship between “focal plane determination criterion values” and “vertical positions of the workpiece table” (which represent the vertical distances from the mark to the camera) having been recorded during the calibration and with the distance from the mark to the camera remaining unknown when the image was captured, the vertical distance from the current vertical position of the workpiece table to the camera can be calculated by maintaining the workpiece table at the current vertical position (i.e, maintaining the distance from the mark to the camera), capturing the image, calculating the “focal plane determination criterion” value and substituting the calculated focal plane determination criterion value into the established relationship. Alternatively, in case of a relationship between “focal plane determination criterion values” and “vertical positions of the mark” being calibrated in step (1), the vertical distance from the mark to the camera at the current vertical position of the workpiece table may be calculated, as well as the vertical distance d from the workpiece table or the mark to the focal plane at the current vertical position of the workpiece table.

With step (4) having been completed, it remains still unknown whether the

workpiece table deviates from the focal plane in the forward or in the reverse direction. Thus, in step (5) of the second method, the workpiece table is moved by respective distances of d and $-d$ from its current vertical position in step (2). That is, it is displaced by the distance of d in each of the directions approaching and going away from the camera. Thereafter, focal plane determination criterion values V_1 and V_2 are calculated for the respective new positions.

In step (6) of the second method, from the comparison made between the focal plane determination criterion values V_1 and V_2 , it is easy to know that the mark is at the optimal focal plane when the workpiece table is located at the vertical position corresponding to the focal plane determination criterion value V_1 or V_2 , whichever is better.

As shown in Fig. 6, assuming that on the surface of the workpiece table, the alignment sub-mark 20 is centered diametrically and equidistantly between a pair of focusing sub-marks, i.e., the center of the alignment sub-mark 20 is located at the midpoint of the line segment interconnecting the centers of the pair of focusing sub-marks, the optimal focal plane position 2 for the alignment sub-mark 20 will be the mean of the optimal focal plane position 1 for one of the focusing sub-marks and the optimal focal plane position 3 for the other of the focusing sub-marks. Here, the optimal focal plane positions for the alignment and focusing sub-marks may be represented by the heights (i.e., vertical coordinates) of their centers with respect to the alignment system. In addition, the tilt of the alignment sub-mark 20 may also be obtained from the optimal focal plane position 1 for one of the focusing sub-marks and the optimal focal plane position 3 for the other of the focusing sub-marks.

An alignment method for the mark comprises the steps as explained in detail below.

In step (1), a workpiece on which n sets of marks with a focusing and

tilt-correction design have been formed is placed on a workpiece table and then a focusing and leveling system (FLS) is used to carry out a first focusing and leveling process thereon.

Referring to Fig. 7, in this Embodiment, three (i.e., $n=3$) sets of marks with a focusing and tilt-correction design, referred hereinafter to respectively as the first set of marks, the second set of marks and the third set of marks, are formed on the workpiece. In each of the sets of marks, the alignment sub-mark is located diametrically and equidistantly between each pair of focusing sub-marks.

In step (2), the workpiece table is moved so that the sets of marks are displaced into the field of view of the alignment system, followed by an initial alignment and measurement for obtaining horizontal position information of the focusing sub-marks in the sets of marks.

In step (3), the workpiece table is moved vertically by a predetermined distance, and for each of the sets of marks, the optimal focal plane positions $\{P_i, Q_i\}$ for the at least one pair of focusing sub-marks are obtained using their focal plane determination criterion values and an optimal focal plane determination method, i.e., the first or second method described above.

Wherein, P_i and Q_i are the respective optimal focal plane positions for one pair of focusing sub-marks in the i -th set of marks, $i=1, 2, \dots, n$, and $n \geq 3$.

According to this Embodiment, there are obtained in this step: the optimal focal plane positions P_1, Q_1 for one pair of focusing sub-marks in the first set of marks; the optimal focal plane positions P_2, Q_2 for one pair of focusing sub-marks in the second set of marks; and the optimal focal plane positions P_3, Q_3 for one pair of focusing sub-marks in the third set of marks.

In step (4), for each of the sets of marks, an initial optimal focal plane position value M_i for the alignment sub-mark 20, as well as an initial tilt value T_i thereof, is

obtained based on the optimal focal plane positions $\{P_i, Q_i\}$ for the pair of focusing sub-marks, namely, the vertical positions of the optimal focal planes for the two focusing sub-marks, as well as on a horizontal distance $Dis(P_i, Q_i)$ corresponding to the set of marks.

$$\text{Wherein } M_i = \frac{P_i + Q_i}{2}, \text{ and } T_i = \arctan\left(\frac{P_i - Q_i}{Dis(P_i, Q_i)}\right).$$

In this step, with reference to Fig. 7, the optimal focal plane position M_1 and tilt T_1 of the alignment sub-mark in the first set of marks can be obtained based on the optimal focal plane positions P_1, Q_1 , the optimal focal plane position M_2 and tilt T_2 of the alignment sub-mark in the second set of marks can be obtained based on the optimal focal plane positions P_2, Q_2 , and the optimal focal plane position M_3 and tilt T_3 of the alignment sub-mark in the third set of marks can be obtained based on the optimal focal plane positions P_3, Q_3 .

In step (5), based on the initial optimal focal plane position values M_i and initial tilt values T_i for the alignment sub-marks 20, an optimal focal plane position M and tilt T for the workpiece (wafer) that is located within an FOV area delimited by the multiple alignment sub-marks 20 are determined using mean filtering or median filtering.

In step (6), the workpiece table is moved vertically based on the optimal focal plane position M and tilt T of the workpiece (wafer) located within in the FoV so as to compensate for the vertical positions of those alignment sub-marks that need to be compensated for.

In step (7), with reference to Fig. 8, the horizontal positions x_{wzcs}, y_{wzcs} of the alignment sub-marks 20 are recalculated and the position of the workpiece table during the measurement is recorded. After the displacement of the workpiece table in step (6), the marks with a focusing and tilt-correction design are now located at new horizontal positions as shown in Fig. 8 (though the specific trajectory and positional

evolution are not shown in the figure), i.e., the horizontal position X_1 , Y_1 of the first set of marks, the horizontal position X_2 , Y_2 of the second set of marks and the horizontal position X_3 , Y_3 of the third set of marks.

In step (8), the position of the workpiece (wafer) on the workpiece table is obtained.

Step (1) constitutes a first focusing and leveling process for initial adjustment, while steps (3)-(8) is a second focusing and leveling process for high-precision focusing and leveling of the alignment sub-marks.

It is noted that in case of each of the n sets of marks comprising multiple (e.g., m) pairs of focusing sub-marks, the optimal focal plane position calculation may be performed either on one pair of focusing sub-mark in each set of marks or on two or more pairs of focusing sub-marks in each set of marks. In the latter case, the collection $\{P_{ij}, Q_{ij}\}$ is obtained, wherein $i=1, 2, \dots, n$, and $j=1, 2, \dots, m$. And then, for example, for each set of marks, the optimal focal plane positions of the two or more pairs of focusing sub-marks may be averaged to obtain the mean optimal focal plane positions P_i and Q_i which represent the optimal focal plane positions of the whole set of marks. This approach is particularly suitable for the scenarios where the focusing sub-marks are grating-like marks. As shown in Fig. 7, when grating-like marks are used, each set of marks typically includes two pairs of such marks with their grating bands perpendicular to each other (e.g., a pair of grating-like marks with vertical grating bands and a pair of grating-like marks with horizontal grating bands), and their calculated optimal focal plane positions are averaged. However, for square or other marks, it is not necessary to have more than one pair of them and to perform the averaging operation thereon.

The above section presents the mark with a tilt-correction design as well as the alignment method thereof, but does not take into account the impact of distortion on

alignment accuracy of the alignment sub-mark.

As shown in Fig. 9, the alignment sub-mark has a certain width, exemplified as the width of the line segment LR in the figure. The alignment sub-mark has two lateral positions L and R and a central position C, which are actually imaged respectively to L', R' and CC. A calibration algorithm can be used to establish a relationship between ideal and actual image positions, as indicated by the arrows in Fig. 9. Due to the non-linear nature of distortion, the position CC deviates from the ideal position C'. That is, there is a deviation from the actually measured position CC of the mark from the position where it is supposed to be. Nevertheless, if the deviation is a fixed value, the reproducibility could still be ensured. However, in fact, as the deviation varies with the FoV position, the measurement reproducibility is affected.

A method for calculating the impact of distortion on alignment accuracy comprises the steps of:

- (1) plotting a curve $O(t)$ of deviation of the camera from its ideal image position vs. FoV position using optical design software such as Zemax and CODE V;
- (2) creating a window function with a width T based on the mark width;
- (3) equally splitting the window into two adjacent sub-windows $W(t)$ and $W(t-T/2)$ each having a width of $T/2$;
- (4) convolving the sub-windows $W(t)$ and $W(t-T/2)$ respectively with $O(t)$ to obtain $C(t)$ and $D(t)$;
- (5) calculating $E(t)=C(t)-D(t)$; and
- (6) finding the maximum value Max and minimum value Min in $E(t)$.

Impact of distortion on accuracy on the image side can be calculated as $Err=Max-Min$, while the corresponding value on the object side is equal to $Err/magnification$.

As apparent from the above analysis, the smaller the width of the alignment sub-mark 20 is, the less the impact of distortion on accuracy will be. However, since CCD (Charge Coupled Device)-based image discretization is to be performed subsequently, the width of the alignment sub-mark 20 needs to be greater than the size of discretized image particles. Therefore, the alignment sub-mark 20 could not be arbitrarily small.

In addition, in the alignment sub-mark 20, features indicative of its position exist only in its edge portion and are absent from its constant-brightness central portion. Accurate identification of the edge portion requires four sampling sites within the area thereof (i.e., within the range of the PSF width). Therefore, the width of the alignment sub-mark 20 also needs to be greater than two times the PSF width. In this way, the width of the alignment sub-mark 20 is determinable.

EMBODIMENT 2

This Embodiment differs from Embodiment 1 in that the center of the alignment sub-mark is not necessarily situated at the midpoint of any of the line segments interconnecting the respective pairs of focusing sub-marks (as shown in Fig. 10). In this Embodiment, the mark includes a pair of square focusing sub-marks 10' and 30', a pair of horizontal-grating-like focusing sub-marks 11' and 31' and a pair of vertical-grating-like focusing sub-marks 12' and 32', and the center of the alignment sub-mark 20' is not located at the midpoint of any of the line segments interconnecting the respective pairs of focusing sub-marks. Instead, the distances of the center to the focusing sub-marks are known. Specifically, for example, the distances $W1W2$ and $W2W3$ from the alignment sub-mark to the focusing sub-marks are known, as shown in Fig. 10. From these known distances, the optimal focal plane position for the alignment sub-mark is determinable. As compared to that of Embodiment 1, the mark according to this Embodiment is subject to fewer limitations

and can thus better satisfy the requirements of users.

The rest of the mark except what is described above and how it is aligned, according to this Embodiment, are the same as those of Embodiment 1, and further description in this regard is omitted herein for the sake of clarity and simplicity.

EMBODIMENT 3

This Embodiment differs from Embodiment 1 in that the alignment sub-mark consists of horizontal or vertical bars for unidirectional position measurement, as shown in Fig. 11. In this Embodiment, the mark includes a pair of square focusing sub-marks 10" and 30", a pair of horizontal-grating-like focusing sub-marks 11" and 31" and a pair of vertical-grating-like focusing sub-marks 12" and 32", and the center of the alignment sub-mark 20" is not located at the midpoint of any of the line segments interconnecting the respective pairs of focusing sub-marks. As compared to that of Embodiment 1, the mark according to this Embodiment enables unidirectional position measurement and can satisfy additional requirements of users.

The rest of the mark except what is described above and how it is aligned, according to this Embodiment, are the same as those of Embodiment 1, and further description in this regard is omitted herein for the sake of clarity and simplicity.

EMBODIMENT 4

This Embodiment differs from Embodiment 1 in that the alignment sub-mark assuming the shape of a plain cross superimposed with a diagonal cross. As compared to that of Embodiment 1, the mark according to this Embodiment (not shown) can satisfy additional requirements of users.

The rest of the mark except what is described above and how it is aligned, according to this Embodiment, are the same as those of Embodiment 1, and further description in this regard is omitted herein for the sake of clarity and simplicity.

In summary, the mark with a focusing and tilt-correction design and the

alignment method according to the present invention allow high-precision focusing and leveling of the alignment sub-mark. On the one hand, measurement reproducibility is improved by focusing realization and tilt elimination. On the other hand, it is presented herein an analysis of how distortion impacts measurement reproducibility, from which constraints for mark width can be derived, resulting in a further improvement in measurement reproducibility.

The foregoing description presents merely a few preferred embodiments of the present invention and does not limit the scope thereof in any sense. All equivalent substitutions or modifications made to the subject matter or features thereof disclosed herein by any person of ordinary skill in the art without departing from the scope of the present invention fall within the scope.

Claims

1. A mark with a focusing and tilt-correction design, comprising an alignment sub-mark and at least one pair of focusing sub-marks, the alignment sub-mark being centered on any one of line segments interconnecting the respective at least one pair of focusing sub-marks, wherein focusing and leveling of the alignment sub-mark is enabled by determining positions of optimal focal planes for the at least one pair of focusing sub-marks.

2. The mark of claim 1, wherein the alignment sub-mark assumes a shape of a plain cross, a plain cross superimposed with a diagonal cross, horizontal bars or vertical bars.

3. The mark of claim 1, wherein the alignment sub-mark is centered at a midpoint of any one of the line segments interconnecting the respective at least one pair of focusing sub-marks.

4. The mark of claim 1, wherein the alignment sub-mark has a width that is greater than a size of discretized particles.

5. The mark of claim 4, wherein the width of the alignment sub-mark is greater than two times a Point Spread Function (PSF) width.

6. The mark of claim 1, wherein the focusing sub-marks resemble squares or gratings.

7. The mark of claim 6, wherein the gratings are horizontal or vertical gratings.

8. The mark of claim 1, wherein the at least one pair of focusing sub-marks comprise a pair of square focusing sub-marks, a pair of horizontal-grating-like focusing sub-marks and a pair of vertical-grating-like focusing sub-marks.

9. An alignment method, comprising the steps of:

(1) providing on a workpiece n sets of marks each having a focusing and tilt-correction design and comprising an alignment sub-mark and at least one pair of

focusing sub-marks, wherein the alignment sub-mark is centered on any one of line segments interconnecting the respective at least one pair of focusing sub-marks;

(2) performing an initial alignment on each set of marks by an alignment system;

(3) vertically stepping a workpiece table by a predetermined distance and, for each set of marks, obtaining optimal focal plane positions $\{P_i, Q_i\}$ for the at least one pair of focusing sub-marks using focal plane determination criterion values and an optimal focal plane determination method, wherein P_i and Q_i represent the optimal focal plane positions for one pair of focusing sub-marks in an i-th set of marks, where $i=1, 2, \dots, n$ and $n \geq 3$;

(4) for each set of marks, obtaining an initial optimal focal plane position value M_i and an initial value for the alignment sub-mark based on the optimal focal plane positions $\{P_i, Q_i\}$ for the at least one pair of focusing sub-marks as well as on a horizontal distance $Dis(P_i, Q_i)$ corresponding to the set of marks, wherein

$$M_i = \frac{P_i + Q_i}{2}, \text{ and } T_i = \arctan\left(\frac{P_i - Q_i}{Dis(P_i, Q_i)}\right);$$

(5) determining an optimal focal plane position M and tilt T of the workpiece using mean filtering or median filtering method based on the initial optimal focal plane position values M_i and initial tilt values T_i of the alignment sub-marks; and

(6) moving the workpiece table vertically based on the optimal focal plane position M and tilt T of the workpiece so as to compensate for the vertical positions of the alignment sub-marks.

10. The alignment method of claim 9, wherein the focal plane determination criterion comprises a gradient amplitude and a PSF width.

11. The alignment method of claim 10, wherein the focusing sub-marks resemble squares or gratings.

12. The alignment method of claim 11, wherein the focal plane determination

criterion for each focusing sub-mark resembling a grating is a gradient amplitude of an image of the sub-mark.

13. The alignment method of claim 11, wherein the focal plane determination criterion for each focusing sub-mark resembling a square is a PSF width of an image of the sub-mark.

14. The alignment method of claim 9, wherein obtaining the optimal focal plane positions $\{P_i, Q_i\}$ for the at least one pair of focusing sub-marks in each set of marks comprises:

- (1) stepping the workpiece table by a predetermined distance;
- (2) capturing an image of the workpiece table after each stepping in a vertical direction;
- (3) calculating focal plane determination criterion values from the captured images; and
- (4) determining the optimal focal plane positions of the at least one pair of focusing sub-marks from a fitted curve.

15. The alignment method of claim 9, wherein obtaining the optimal focal plane positions $\{P_i, Q_i\}$ for the at least one pair of focusing sub-marks in each set of marks comprises:

- (1) calibrating and establishing a relationship between focal plane determination criterion values and vertical positions of the workpiece table;
- (2) capturing an image of the workpiece table at a current vertical position thereof ;
- (3) calculating the focal plane determination criterion value from the captured image;
- (4) obtaining a distance d from the current vertical position of the workpiece table from a focal plane based on the established relationship between the focal plane

determination criterion values and vertical positions of the workpiece table as well as on the calculated focal plane determination criterion value;

(5) vertically moving the workpiece table by respective distances of d and $-d$ from the current vertical position thereof and capturing images of the workpiece table at respective new positions, based on which focal plane determination criterion values V_1 and V_2 are calculated; and

(6) determining the optimal focal plane positions for the at least one pair of focusing sub-marks by comparing V_1 with V_2 .