



(51) International Patent Classification:
G03F 7/20 (2006.01)

(21) International Application Number:
PCT/EP2017/084276

(22) International Filing Date:
21 December 2017 (21.12.2017)

(25) Filing Language: English

(26) Publication Language: English

(30) Priority Data:
10 2016 226 083.9
22 December 2016 (22.12.2016) DE

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(81) Designated States (*unless otherwise indicated, for every
kind of national protection available*): AE, AG, AL, AM,
AO, AT, AU, AZ, BA, BB, BG, BH, BN, BR, BW, BY, BZ,
CA, CH, CL, CN, CO, CR, CU, CZ, DE, DJ, DK, DM, DO,
DZ, EC, EE, EG, ES, FI, GB, GD, GE, GH, GM, GT, HN,
HR, HU, ID, IL, IN, IR, IS, JO, JP, KE, KG, KH, KN, KP,
KR, KW, KZ, LA, LC, LK, LR, LS, LU, LY, MA, MD, ME,
MG, MK, MN, MW, MX, MY, MZ, NA, NG, NI, NO, NZ,
OM, PA, PE, PG, PH, PL, PT, QA, RO, RS, RU, RW, SA,

(54) Title: TRAJECTORY FITTING

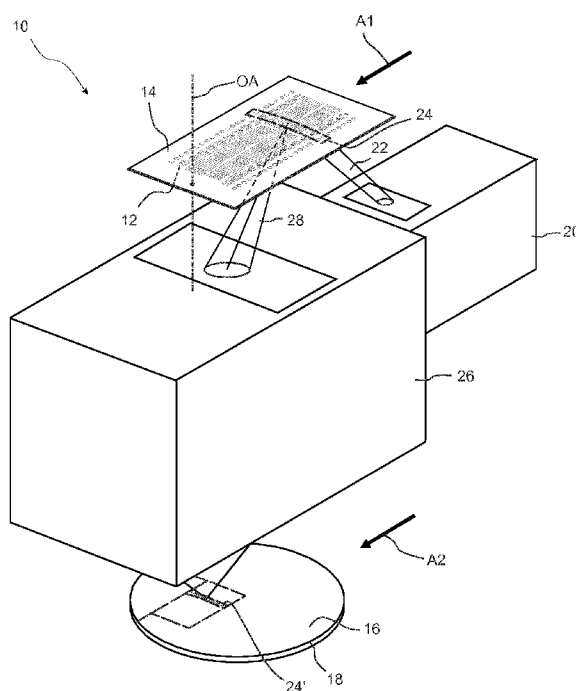


Fig. 1

(57) **Abstract:** The invention relates to a method for controlling an optical element of an optical arrangement for a microlithographic projection exposure apparatus, the method comprising providing an optical element and at least one actuator configured to move and/or deform the optical element in at least one degree of freedom, controlling movement and/or deformation of at least one point of the optical element along a trajectory during at least one exposure trajectory segment and during at least one non-exposure trajectory segment, wherein the non-exposure trajectory segment is defined such that at least one of the following parameters is minimized along the exposure trajectory segment: control error, actuator force, power. The invention also relates to a microlithographic projection exposure apparatus comprising an optical element, at least one actuator configured to move and/or deform the optical element in at least one degree of freedom and a control device, wherein the control device is adapted to perform the above mentioned method.

SC, SD, SE, SG, SK, SL, SM, ST, SV, SY, TH, TJ, TM, TN,
TR, TT, TZ, UA, UG, US, UZ, VC, VN, ZA, ZM, ZW.

- (84) Designated States** (*unless otherwise indicated, for every kind of regional protection available*): ARIPO (BW, GH, GM, KE, LR, LS, MW, MZ, NA, RW, SD, SL, ST, SZ, TZ, UG, ZM, ZW), Eurasian (AM, AZ, BY, KG, KZ, RU, TJ, TM), European (AL, AT, BE, BG, CH, CY, CZ, DE, DK, EE, ES, FI, FR, GB, GR, HR, HU, IE, IS, IT, LT, LU, LV, MC, MK, MT, NL, NO, PL, PT, RO, RS, SE, SI, SK, SM, TR), OAPI (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, KM, ML, MR, NE, SN, TD, TG).

Published:

- *with international search report (Art. 21(3))*
 - *before the expiration of the time limit for amending the claims and to be republished in the event of receipt of amendments (Rule 48.2(h))*
-

Trajectory Fitting

BACKGROUND OF THE INVENTION

1. Field of the invention

The invention relates to a method for controlling an optical element of an optical arrangement of a microlithographic projection exposure apparatus which may be configured, for example, for wavelengths in the extreme ultraviolet spectral range (EUV). The optical arrangement may be contained in an illumination system or a lens of such an apparatus. The
5 invention also relates to a microlithographic projection exposure apparatus.

2. Description of prior art

Microlithographic projection exposure apparatuses are used to transfer structures arranged on a mask – also called reticle – to a light-sensitive layer such as a photoresist, for example. The light-sensitive layer is usually situated on a wafer or some other substrate. The projection exposure apparatus typically comprises a light source, an illumination system, which projection light generated by the light source and directs it onto the mask, and
10 a lens, which images the mask illuminated by the projection light onto the light-sensitive layer.

The shorter the wavelength of the projection light, the smaller the structures which can be produced on the light-sensitive layer with the aid of the projection exposure apparatus.
15 The most recent generation of projection exposure apparatuses uses projection light having a centre wavelength of approximately 13.5 nm, which is thus in the extreme ultraviolet spectral range (EUV). Such apparatuses are often referred to as EUV projection exposure apparatuses.

However, there are no optical materials which have a sufficiently high transmissivity for
20 such short wavelengths. Therefore, in EUV projection exposure apparatuses the lens elements and other refractive optical elements that are customary at longer wavelengths are replaced by mirrors, and the mask therefore contains a pattern of reflective structures.

The mirrors comprise a mirror substrate having a reflection region, which is formed on a surface of the mirror substrate and in which the mirror substrate bears a reflective coating. The mirrors are often fixed in support frames that are connected to a rigid frame structure of the lens or of the illumination system via actuators. The entire, inherently rigid assembly comprising a mirror and, if appropriate, supporting frames fixed thereto, or other components, is referred to hereinafter as mirror element.

The mirror elements of the illumination system direct the projection light onto the mask; the mirror elements of the lens image the region illuminated on the mask onto the light-sensitive layer.

10 In order to accomplish this with the required accuracy, the reflection regions of the mirror elements have to be aligned precisely with one another in all six degrees of freedom. Electrically actuable actuators are usually used for positioning and aligning the mirror elements.

15 EUV projection exposure apparatuses having a large numerical aperture require mirror elements having a large diameter. Such mirror elements are costly to produce and, owing to their high inherent weight, make it more difficult to implement mounting and actuation with little deformation. Since the mirror element is not an ideal rigid body, the shape of the mirror substrate can vary, e.g. in the long term on account of material degradations and in the short term as a result of the influence of forces and moments that act on the mirror substrate during actuation.

In EUV projection exposure apparatuses, a mirror may be actuated by means of a hexapod, i.e. a parallel manipulator comprising six actuators for controlling position and orientation of the mirror in space. Further, a number of sensor elements may be provided for sensing position, acceleration, etc. of the mirror.

25 Usually, the light-sensitive layer, e.g. the photoresist, contains a number of adjacent target fields to be exposed successively. During the exposure process of a portion of the light-sensitive layer, a number of errors caused e.g. by reticle heating, wafer heating, reticle and/or wafer clamping may arise. Such effects become more critical due to both stricter

requirements for overlay and higher-order surface deformations, as well as increasing heat fluxes and heat loads. One known method for correction of such effects dynamically during exposure is to correct the expected error by driving optical elements in the system in the opposite direction. Errors that have to be corrected during exposure are generally not
5 constant over one particular exposure field and may vary additionally from field to field of a given wafer.

Accordingly, it is an object of the present invention to provide a method for controlling an optical element of an optical arrangement for a microlithographic projection exposure apparatus and a microlithographic projection exposure apparatus providing an approach for
10 reducing errors and to increase accuracy for a single exposure of a field of a wafer and for a series of exposures for a given wafer.

SUMMARY OF THE INVENTION

This object is achieved by means of a method for controlling an optical element of an optical arrangement for a microlithographic projection exposure apparatus, the method comprising: providing an optical element and at least one actuator configured to move
15 and/or deform the optical element in at least one degree of freedom; controlling movement and/or deformation of at least one point of the optical element along a trajectory during exposure and during non-exposure - also termed as "dark-time", wherein the non-exposure trajectory segment is defined such that at least one of the following parameters is minimized along at least the exposure segment of the trajectory and/or along the total
20 trajectory segment: acceleration, jerk, snap, control error, actuator force, power.

The term "optical element" shall comprise any type of optical element influencing the propagation or quality of light, e.g. a refractive or diffractive lens, a mirror, a prism, a filter, a grating, etc. Further, the method may be implemented also at other positions, e.g. at a reticle, a wafer, etc.

25 The term "actuator" shall comprise any object, element, arrangement, system or field adapted to exert actively or passively a force on the optical element for controlling the

movement or deformation of the optical element. Controlling the movement or the deformation of the optical element shall also comprise retaining a present state without movement or deformation. The actuator may comprise, for example, a force actuator or a displacement actuator.

- 5 The term "a point of an optical element" shall comprise any actual or virtual point correlated with the optical element, e.g. a point of interest, point of control, center of mass, a surface feature etc.

The term "trajectory" shall comprise a time-ordered set of states of the dynamical system comprising the optical element. Trajectory shall comprise a time-ordered set of positions
10 the point of the optical element is presently following. A state may include information such as position, and/or orientation, and/or shape such as deformation shape. The dynamical system shall comprise the optical element, the actuators, the sensors, a controller and/or a control scheme (e.g. a feedforward control scheme).

Control error is a deviation of the actual trajectory from a reference trajectory and may
15 comprise position, velocity, acceleration, jerk, snap or other position-related, movement-related, and/or state-related parameters.

Velocity is the first derivative of the trajectory with respect to time of the at least one point of the optical element.

Acceleration is the second derivative of the trajectory with respect to time of the at least
20 one point of the optical element. Acceleration may refer to translational or rotational movements.

Jerk is the third derivative of the trajectory with respect to time of the at least one point of the optical element.

Snap is the fourth derivative of the trajectory with respect to time of the at least one point
25 of the optical element.

The term "power" shall comprise the power required for moving and/or deforming the optical element. The power or energy used for movement or deformation may contribute to

heating the optical element or any surrounding parts, portions of elements of the micro-lithographic projection exposure apparatus, which may in turn increase the heat load.

The term "minimize" shall comprises any form of optimisation along the exposure trajectory. Usually, minimize comprises also the maximum value over the exposure segment or
5 over all segments, i.e. the total trajectory segment.

The term "total trajectory segment" shall comprise all segments of the trajectory which are considered. The total trajectory segment may not necessarily be continuous.

It is a finding of the present invention that the trajectory of the optical element during non-exposure time or dark-time may have a substantial influence on the error arising dur-
10 ing exposure times. Accordingly, it is proposed to move or deform the optical element during a dark-time phase such that certain parameters are minimized in the exposure time phase. The trajectory of the exposure phase may be predefined, whereas the trajectory of the non-exposure phase is to be optimized regarding the positional control error, the maximum actuator force and/or the power. In other words, when optimizing a trajectory
15 for the exposure phase, e.g. for reducing errors, the trajectory of the optical element, i.e. the trajectory of at least one point of the optical element, during a dark-time phase should be taken into account.

For example, one would want to minimize control error during the exposure trajectory (e.g. a scan), but ideally would want to both minimize error during the exposure trajectory
20 and to minimize actuator force and/or power during the non-exposure trajectory.

In particular, it is regarded as beneficial to perform the optimization process of a non-exposure trajectory before defining the exposure trajectory or to perform the optimization of the non-exposure trajectory together with the optimization of the exposure trajectory.

In particular, one of the parameters positional control error, maximum actuator force,
25 and/or power may be minimized along exposure trajectory segments.

Preferably, at least one of the parameters is minimized along all trajectory segments. Minimizing one or more of the parameters along the entire trajectory of the at least one point

of the optical element during exposure and during non-exposure is expected to result in a minimum error for the exposure phases. In particular, the actuator power and/or the force during a non-exposure trajectory segment may be limited, i.e. minimized to remain below a certain threshold and the control error, in particular the positional control error, may be
5 minimized during an exposure trajectory segment.

According to an embodiment the non-exposure trajectory segment is a polynomial fit or a spline fit. The spline fit may be based on b splines, cubic splines or non-uniform rational b-splines ("NURBS"). The derivation of the fit may be based on the complete trajectory or on segments of the trajectory. The segments of the trajectory may be defined according to
10 functional considerations, e.g. exposure phase and non-exposure phase.

When the start and endpoint conditions for a defined segment are known, like the non-exposure phase or the exposure phase, a polynomial fit over the entire segment may be defined using the known boundary conditions. It is also possible to divide a segment into defined time intervals. The time intervals may be discrete time intervals with a fixed length
15 of time or may be defined having varying but pre-defined time lengths. The conditions may then be set within the intervals separately.

According to an embodiment two segments are concatenated. The segments may be two non-exposure segments, two exposure segments, or a non-exposure segment and an exposure segments. The order of the non-exposure segment and the exposure segment may
20 be interchanged. The resulting concatenated segment may be of differentiability class C^0 . This implies that the resulting concatenated segment is continuous, i.e. the resulting concatenated segment including two non-exposure segments, two exposure segments, and/or a non-exposure segment and an exposure segment are of continuity C^0 . A differentiability class C^n is defined as follows: A trajectory segment f is of differentiability class C^n if
25 the derivatives f' , f'' , ..., $f^{(n)}$ exist and are continuous. The continuity is implied by differentiability for all the derivatives except for $f^{(n)}$.

In this regard, in a preferred embodiment the resulting concatenated segment is of differentiability class C^n , where $n = 1 \dots 6$. Differentiability class C has been proven to be the best compromise between arithmetical efforts and precision. Of course, a trajectory having

all derivatives continuous, i.e. being smooth, is also within the scope of the present invention.

The intervals may be concatenated together, e.g. with additional rules about the smoothness and how they fit together. The smoothness of the resulting concatenated segment
 5 may refer to a condition including continuity of all derivatives. A lower order of continuity may be acceptable as well.

Preferably, the optical element is controlled by a feedback control and/or by a feedforward control concerning the parameter to follow the trajectory. As an example, the trajectory of the exposure phase may be predefined, whereas the trajectory of the non-exposure
 10 phase is to be optimized regarding the positional control error, the maximum actuator force and/or the power. During the process of controlling the point of the optical element along the trajectory segment, the actuator movement and/or deformation the optical element is determined and compared with the intended actuator movement/deformation of the predefined trajectory. The result of the comparison is the deviation of the actual tra-
 15 jectory from the predefined model trajectory. To maintain the deviation below a specified value, the control may comprise a feedback control and/or a feedforward control. One or more of the following signals may be used for feedback: position, velocity, acceleration, jerk, snap, or higher order derivations with respect to time of the position. The feedback is, however, not limited to this set. It is also possible that multiple signals, i.e. more than one
 20 position, more than one acceleration, etc. of the above list are used to define the desired movement of the optical element. According to an embodiment, the feedback control may be according to the equation:

$$F_{FB} = c \cdot e,$$

25 wherein

F_{FB} : feedback force

c : control parameter

$e = r - y$ deviation ("error") of model trajectory r from an actual trajectory y

For compensating known disturbances concerning the trajectory, a feedforward control according to the following equation may be implemented in the case of a mass-related movement of the optical element:

$$F_{FF} = \ddot{r} \cdot m_i$$

- 5 wherein F_{FF} : feedforward force
 $\ddot{r}$: acceleration
 m : mass of the accelerated optical element

The total force exerted on the optical element is:

$$F = F_{FF} + F_{FB}$$

- 10 The above discussed relations are by way of example for the case of moving an optical element having a mass. In the case of a trajectory defined more abstractly according to a time-ordered set of states of the dynamical system comprising the optical element different equations may apply.

- 15 The object is also achieved by means of a microlithographic projection exposure apparatus comprising an optical element, at least one actuator configured to move and/or deform the optical element in at least one degree of freedom and a control device, wherein the control device is adapted to perform at least one of the methods described above.

- 20 According to a preferred embodiment of the apparatus the optical element is a mirror having a mirror substrate and a reflection region formed on a surface of the mirror substrate.

BRIEF DESCRIPTION OF THE DRAWINGS

Further features and advantages of the invention will become apparent from the following description of the embodiments with reference to the drawings, in which

Figure 1 shows in a perspective view a schematic microlithographic EUV projection exposure apparatus comprising an illumination system and a lens;

- Figure 2 shows a meridional section through the lens of the projection exposure apparatus shown in Figure 1;
- Figure 3 shows in a schematic view a model of a scanning mirror including a controller;
- Figure 4 shows in a schematic diagram four segments of an exemplary trajectory for correctable errors with separated contributions;
- Figure 5 shows the diagram of figure 4 with the sum of individual contributions resulting in a total error to be corrected;
- Figure 6 shows in a schematic diagram an example implementation of several segments of a model trajectory;
- Figure 7 shows in a schematic diagram two degrees of freedom of a model trajectory, each represented by fitted polynomial segments and/or interpolated segments; and
- Figure 8 shows in a schematic diagram the calculated error at a point of interest when following the model trajectory as shown in figure 7.

15

DESCRIPTION OF PREFERRED EMBODIMENTS

1. Basic construction of the projection exposure apparatus

Figure 1 shows, in a perspective and highly schematic illustration which is not to scale, the basic construction of a microlithographic projection exposure apparatus 10 according to the invention. The projection exposure apparatus 10 serves to project reflective structures 12 arranged on a side - facing downwards in Figure 1 - of a mask 14 onto a light-sensitive layer 16. The light-sensitive layer 16, which can be, in particular, a photoresist (also called resist), is carried by a wafer 18 or some other substrate.

The projection exposure apparatus 10 comprises an illumination system 20, which illuminates that side of the mask 14 which is provided with the structures 12 with EUV light 22.

A range of between 5 nm and 30 nm, in particular, is appropriate as wavelength for the EUV light 22. In the embodiment illustrated, the centre wave-length of the EUV light 22 is approximately 13.5 nm. The EUV light 22 illuminates an illumination field 24 on the downwardly facing side of the mask 14, said illumination field having the geometry of a ring
5 segment here.

The projection exposure apparatus 10 furthermore comprises a lens 26, which generates on the light-sensitive layer 16 a reduced image 24' of the structures 12 lying in the region of the illumination field 24. The lens 26 has an optical axis OA, which coincides with the axis of symmetry of the ring-segment-shaped illumination field 24, and is thus situated
10 outside the illumination field 24. The illumination field 24 may, of course, have an arbitrary shape. Also, an optical axis OA is not necessarily present.

The lens 26 is designed for scanning operation in which the mask 14 is displaced synchronously with the wafer 18 during the exposure of the light-sensitive layer 16. These displacing movements of the mask 14 and of the wafer 18 are indicated by arrows A1, A2 in Fig-
15 ure 1. During an exposure of the light-sensitive layer 16, the illumination field 24 thus sweeps over the mask 14 in a scanner-like manner, as a result of which even relatively large contiguous structure regions can be projected onto the light-sensitive layer 16. The ratio of the speeds at which the mask 14 and the wafer 18 are displaced is in this case equal to the imaging scale β of the lens 26. In the embodiment illustrated, the image 24'
20 generated by the lens 20 is reduced ($|\beta| < 1$) and erect ($\beta > 0$), for which reason the wafer 18 is displaced more slowly than the mask 14, but in the same direction.

Light beams proceed from each point in the illumination field 24 which is situated in an object plane of the lens 26, said light beams entering into the lens 26. The latter has the effect that the entering light beams converge in an image plane of the lens 26 at field
25 points. The field points in the object plane from which the light beams proceed, and the field points in the image plane in which said light beams converge again are in this case in a relationship with one another which is designated as optical conjugation.

For an individual point in the centre of the illumination field 24, such a light beam is indicated schematically and designated 28. In this case, the aperture angle of the light beam

28 upon entering into the lens 26 is a measure of the numerical aperture NA thereof. On account of the reduced imaging, the image-side numerical aperture NA of the lens 26 is enlarged by the reciprocal of the imaging scale β .

Figure 2 shows important components of the lens 26 likewise schematically and not to scale in a meridional section. Between the object plane indicated at 30 and the image plane indicated at 32, a total of six mirror elements M1 to M6 are arranged along an optical axis OA. Each of the mirror elements M1 to M6 comprises a mirror substrate 34 and a reflection region 36, as is shown by way of example for the mirror element M6. The light beam 28 proceeding from a point in the object plane 30 firstly impinges on a concave first mirror element M1, is reflected back onto a convex second mirror element M2, impinges on a concave third mirror element M3, is reflected back onto a concave fourth mirror element M4 and then impinges on a convex fifth mirror element M5, which directs the EUV light back onto a concave sixth mirror element M6. The latter finally focuses the light beam 28 into a conjugate image point in the image plane 32.

If the mirror elements M1 to M6 were supplemented by the parts indicated by dashed lines in Figure 2, then the reflection regions 36 of the mirror elements thus supplemented would be rotationally symmetrical with respect to the optical axis OA of the lens 26. As can readily be discerned, the beam path described above could not be realized with such completely rotationally symmetrical reflection regions 36, however, since the mirror units M1 to M6 would then partly block the light path. Therefore, the mirror elements M1 to M6 have the shapes indicated by solid lines.

An aperture stop 38 is arranged between the mirror elements M5 and M6.

2. Model of a Scanning Mirror

For discussing the control concept of the present invention, a scanning optical element 40, e.g. a scanning mirror, is discussed in more detail with reference to Figure 3 as an exemplary embodiment. The scanning optical element 40 comprises an optical effective surface 42, e.g. a reflective surface. The scanning optical element 40 is mechanically connected with an actuator 44 comprising six actuator elements 46, e.g. in a hexapod arrangement.

The actuators may for example be electromagnetic actuators. For a different embodiment a different number of actuators 44 and a different kind of actuator may be selected without departing from the present invention.

The scanning optical element 40 further comprises three vertically operating sensor elements 48 and three horizontally operating sensor elements 50. The terms horizontally and vertically refer to the optical effective surface 42 of the scanning optical element 40. Other arrangements in number, position, and/or orientation of sensor elements and other operating directions may apply for a different embodiment without departing from the present invention.

For following the model trajectory, the scanning optical element 40 is controlled by a controller 52. The controller 52 is connected with the six actuator elements 46 and with the four sensor elements 48, 50, indicated by corresponding connection lines. The controller 52 is adapted to provide a feedback control and a feedforward control. The feedforward control may be a mass feedforward, more complex feedforward strategies may be used.

The controller 52 is adapted to provide scanning profiles, i.e. trajectories the mirror should follow, while the light-sensitive layer 16 is illuminated by the illumination system 20. The scanning movements of the scanning optical element 40 are to compensate for certain optical effects, e.g. due to a reticle heating, wafer heating, reticle and/or wafer clamping, possibly arising before or during the scanning process. The scanning movement may be described by referring to at least one point of control (POC) 54 for control purposes and/or to at least one point of interest (POI) 56 for defining a trajectory, as indicated in Fig. 3.

Figure 4 shows in a schematic diagram four segments of an exemplary trajectory for correctable errors with separated contributions. Trajectory following is used to minimize and/or correct system errors during critical time periods of system operation. Particularly in EUV lithography products, it is desired to correct errors caused by reticle heating, wafer heating, reticle and wafer clamping as well as of the effects generally denominated as correctables.

For correcting the optical effects caused by these errors dynamically during exposure, the expected error is corrected by driving the scanning optical element 40 of the apparatus 10 in a direction allowing to compensate for the adverse effect.

The errors that have to be corrected during exposure are generally not constant over time, e.g. one particular exposure field like a die, and are not constant over many dies that are produced on a given wafer. Accordingly, a desired trajectory is defined for one or more degrees of freedom of the scanning optical element 40. The trajectory during exposure accounts for the sum of all errors that ideally have to be corrected. It is possible that the desired, i.e. the ideal, trajectory is reduced in complexity by reducing the polynomial order, the frequency content or the number of degrees of freedom to minimize system complexity, but the general target is to provide an acceptable amount of . This method of correction can be considered for one mechatronic system, for one optical element such as the scanning optical element 40, e.g. a mirror, and/or for several optical elements, e.g. one or some of the mirrors M1 to M6 as described above.

Figures 4 and 5 give an example of this approach. In Figure 4, two separate contributions of different errors are shown as error portions of a total error, which is shown in Figure 5. The error contributions of Figure 4 are a result of model calculations and/or measurements and take into account reticle heating resulting in a displacement of the reticle and wafer heating resulting in a displacement of the wafer. Other influences may be, for example, clamp heating resulting in a change of the clamp force exerted on the wafer, which in turn may result in a displacement of the wafer, or other contributions, which may be measured influences for a specific setup that may not be readily attributed to an identifiable mechanism.

The mentioned contributions are shown in a diagram in Figure 4 for two consecutive exposure time periods. In the diagram, the abscissa shows the time in arbitrary units, and the ordinate shows a one-dimensional trajectory of the respective element for correcting the error resulting during exposure/non-exposure time periods. Of course, for correcting the error induced by one element – e.g. reticle, wafer, etc. – more than one dimension may be

necessary to achieve a full error correction. However, for explanation purposes in the context of the present embodiment only a one-dimensional approach is discussed.

In Figure 4, line 401 (solid) shows the contribution of a temperature change to the correction profile during exposure/non-exposure of the reticle, line 403 (dashed) the influence of a temperature change during exposure/non-exposure of the wafer. An exposure time period 407, 408 follows a non-exposure time period 405, 406.

As can be seen from Fig. 4, during the first exposure period 407, the reticle heating requires a substantial error correction. Right after the beginning of the exposure period 407, the trajectory 401 reaches a first value 4011. From this first value 4011, the trajectory 401 rises continuously and reaches a second value 4012, the second value being higher than the first value 4011. At this point of time, the first exposure period 407 ends. Thus, the influences caused by the exposure process – mainly heat input – end and the correction portion of the trajectory may be substantially reduced.

In the non-exposure period 406, the trajectory 401 is at the low level that had been reached with the end of the exposure period 407. This means, that concerning the contribution to the correction profile, here for the compensation of the reticle heating, there is no requirement. However, it may still be necessary perform other corrections, e.g. to move the reticle to a next field (step-and-scan). The beginning of the new exposure period 408 requires the trajectory 401 to rise again to a third value 4013, the third value 4013 being of a similar height a the second value 4012.

During the second exposure period 408, the trajectory 401 again compensates for the influences caused by the exposure process. However, in contrast to the first exposure period 407, the influences caused by the reticle are getting smaller during the exposure process. Thus, the trajectory portion 401 falls during the exposure period 408 from the third value 4013 to a fourth value 4014, the fourth value 4014 being smaller than the third value 4013.

The second trajectory 403, representing the wafer influences to be corrected, shows during the first non-exposure period 405 and during the first exposure period 407 a general similar development. The correction amount of the second trajectory 403 during the first

exposure period 407 is smaller. Accordingly, the second trajectory 403 reaches at the beginning of the exposure period 407 a first value 4031, the first value 4031 of the second trajectory 403 being smaller than the first value 4011 of the first trajectory 401. During the exposure process of the first exposure period 407, the second trajectory 403 increases
5 continuously and reaches a second value 4032, the second value 4032 of the second trajectory 403 being higher than the first value 4031. At the end of the exposure period 407, the major influences of the exposure process diminishes and the second trajectory 403 reaches a minimum level.

The minimum level is maintained during the non-exposure period 406. At the beginning
10 of the second exposure period 408, the second trajectory 403 reaches a third value 4033, the third value 4033 being higher than the second value 4032 of the second trajectory 403. During the exposure process of the second exposure period 408, the trajectory rises again and reaches a fourth value 4034, which is again higher than the third value 4033 of the second trajectory 403

15 The first and second trajectories 401, 403 are regarded as trajectory portions of a "sum" or "total" trajectory 501, as can be seen in Fig. 5. Fig. 5 shows a total trajectory 501, which represents the actual trajectory the scanning optical element is to follow. The total trajectory 501 includes all contributions of the individual influences, discussed above as first and second trajectories 401, 403.

20 As already mentioned with regard to Fig. 4, the time period under discussion comprises first and second non-exposure periods 505, 506 and exposure periods 507, 508.

Comparing the first and second trajectories 401, 403 of Fig. 1 with the total trajectory 501 of Fig. 5, it is evident that the first and second trajectories 401 and 403 do not add up to the total trajectory 501. Accordingly, further contributions like clamp induced influences or
25 other influences are not discussed here individually in detail. The total trajectory 501 of Fig. 5, however, shows the actual trajectory the scanning optical element 40 has to perform during exposure periods 507, 508.

It is a basic concept of the present invention to take into account the non-exposure periods 505, 506 before, between, and/or after exposure periods 507, 508 for optimizing the trajectory in the non-exposure phase such that the control error, the actuator force, and/or the power is minimized during the whole time, at least during one or more exposure trajectory segments and/or during one or more non-exposure trajectory segments. For example, there may be a requirement on error during an exposure trajectory segment, but there may also be limits in realistic errors, forces, and/or power over all trajectory segments.

Fig. 6 shows the result of an optimisation of total trajectory by considering non-exposure periods. The diagram of Fig. 6 shows on the abscissa a time scale, the ordinate shows a parameter of a trajectory, e.g. a z-coordinate of a scanning optical element 40. In the diagram, a trajectory 601 is shown as a result of a minimisation of an error parameter, e.g. a positional error, during exposure periods and during non-exposure period. The dotted segments 603, 605, 607, 609 correspond to the total trajectory 501 during exposure periods, whereas the solid segments 602, 604, 606, 608 represent trajectory segments during non-exposure time periods. As can be seen from Fig. 6, before the first exposure period during the trajectory segment 603, the first non-exposure, trajectory segment 602 performs a substantial movement/change of states in order to minimise a positional error for example. The same holds for the second non-exposure segment 604, the third non-exposure segment 606, and the fourth non-exposure segment 608. All of the mentioned non-exposure segments 602, 604, 606, 608 are designed to optimise the total trajectory 601 regarding certain parameter, e.g. to achieve a minimum acceleration, to minimise jerk to minimise a positional control error or to minimise the required power, to mention a few.

The trajectory 601 of Fig. 6 is a piecewise second order polynomial fit for one dimension of a positional scan parameter, i.e. the second order polynomial fitting is done in each exposure period. In the non-exposure periods, the fitting is performed with a higher order polynomial. The optimisation observes certain boundary conditions like the maximum force applicable, the response speed of the system, or the like. For example, a polynomial (or any other appropriate type) curve fitting – interpolation or smoothing – is performed on the data during the exposure segments. The result is concatenated with a polynomial

during the non-exposure segments. The polynomial during non-exposure may, for example, be a interpolation, since no "in-between" data points are determined.

Fig. 7 shows a series of exposure scans, i.e. repetitive trajectories of the optical scanning element 40. In the diagram of Fig. 7, the abscissa is a time axis, the unit being seconds.

- 5 The ordinate is a characteristic parameter of a degree of freedom of the scanning optical element 40, e.g. a length unit, here nanometer. The time axis is divided by the scans of the scanning optical element 40 inter-exposure periods and non-exposure periods. Each scan starts at a vertical dashed line and ends at a dash-and-dot line. In the diagram, two trajectories 701, 702 for two example degrees of freedom are shown as a solid line (701) and a
- 10 dashed line (702). The trajectories 701, 702 of the non-exposure segments are the result of a polynomial fitting having an order of six, whereas the polynomials in the exposure segments are of second order. The piecewise segments are concatenated. Higher order polynomials may be chosen to minimise jerk and/or other higher order derivatives of changing position during the dark phase.
- 15 Preferably, the order of the polynomial fitting/interpolation is at least two, preferably between four and seven.

What such a selection of trajectories 701, 702 achieves during the non-exposure periods is to ensure that a starting point of a trajectory during a scan, i.e. an exposure period, not only the system is positioned in the right place with a correct velocity, but is pointing in

20 the correct direction and/or to correct higher order boundary conditions as for example acceleration. This is essentially creating a smooth or continuous curve at the beginning of a scanning portion of the trajectories 701, 702 and may provide a scan velocity that minimises errors such as a positional overshoot, for example. Whereas smooth assumes all derivatives to be continuous, in the present context one may prefer have the curve defined

25 based on continuity. It is preferred to have a continuity of order 0 at least, but order 1 and higher is desired.

During the exposure periods the trajectories 701, 702 are defined by corrections needed by the systems and/or by the customer. Between the exposure period, i.e. during the non-exposure periods, the trajectories 701, 702 are defined so as to minimise position errors. In

addition to instead of minimising positional errors, other targets for the control system may also apply, such as to minimise acceleration, to minimise jerk, to minimise maximum actuator force and/or to minimise the total power required. Such alternative targets could simplify system requirements, allowing to use smaller actuators, creating a smaller total
5 heat load or a heat load that is overall more stable.

Fig. 8, which closely corresponds to Fig. 7, shows in graphs 801, 802 the (residual) control error at the point of interest, i.e. the relevant point of the scanning optical element 40, for trajectories 701, 702 in Fig. 7

Compared to other techniques for fitting over a scan, polynomial fitting is considered to
10 have a number of advantages, although other fitting methods such as defined time intervals between scans may also be considered. A polynomial fitting usually delivers a guaranteed solution to the given problem, may be simply extended, costs a reasonable amount of calculation time and delivers a smooth/continuous solution.

There are several ways to define a desired trajectory route. When the start and end point
15 conditions are defined for defined time segment like the non-exposure period, one can define a polynomial over the entire segment, using non-boundary conditions. Alternatively, one can also break up a segment into defined time intervals. The defined time intervals are discrete time intervals having a fixed length of time or having varying but pre-defined time lengths. Conditions may then be set within these intervals separately. These in-
20 tervals may be blended together for instance with additional rules about their smoothness and how they fit together.

Other possible options for fitting/interpolation besides polynomial may be trigonometric, exponential, or Fourier based.

Further general options for interpolation besides polynomial functions may be B-splines or
25 cubic splines.

There is a variety of options for defining trajectories and interpolating from points, but how one defines the trajectory and/or fit depends on the goal of the motion. Usually one

has to decide whether the accuracy of the path is most important overall, whether the accuracy only at certain points along the paths is important, whether the minimised travelling time is important, etc. Further, the complexity of calculation and of implementation may also be relevant.

- 5 The optimisation/maximisation of certain parameters for a given exposure period trajectory may be achieved by setting a maximum error for each exposure segment, and then defining the trajectory for the non-exposure periods between the already given trajectories for the exposure segments such that the maximum error is not exceeded. On the other hand, it may be preferred that some exposure trajectories (corresponding to exposure fields, e.g. dies) have even better performance at the expense of other exposure tra-
- 10 jectories. Accordingly, one may define the optimisation differently. For example, it may be required that 100% of all exposure trajectories are within a given specification A. Another example may be that 100% of the exposure segments are within specification B wherein specification B is less strict than specification A. But at the same time XX % are also within
- 15 a specification C wherein specification C is tighter than specification A.

The fitting of the trajectories may be performed before a series of exposure periods and may be redefined based on measurements occurring between such series of exposure periods. The series of exposure periods may for example be a wafer.

CLAIMS

1. A method for controlling an optical element of an optical arrangement for a micro-lithographic projection exposure apparatus, the method comprising:
 - providing an optical element and at least one actuator configured to move
5 and/or deform the optical element in at least one degree of freedom,
 - controlling movement and/or deformation of at least one point of the optical element along a trajectory during at least one exposure trajectory segment and during at least one non-exposure trajectory segment, wherein
 - the non-exposure trajectory segment is defined such that at least one of the
10 following parameters is minimized along the exposure trajectory segment and/or a total trajectory segment:

control error, actuator force, power.
2. The method of claim 1, wherein at least one of the parameters is minimized along the non-exposure trajectory segment.
- 15 3. The method of claim 1 or 2, wherein at least one of the parameters is minimized along all trajectory segments.
4. The method of one of the preceding claims, wherein more than one of the parameters and/or more than one of the parameter types are used.
5. The method of one of the preceding claims, wherein the exposure trajectory segment
20 and/or the non-exposure segment is a polynomial fit or a spline fit.
6. The method of claim 5, wherein the polynomial fit or the spline fit of the exposure trajectory is of a linear/second order or higher.
7. The method of claim 5, wherein the polynomial fit or the spline fit of the non-exposure trajectory is of order six or higher.
- 25 8. The method of one of the preceding claims, wherein two segments are concatenated, wherein the resulting concatenated segment is of differentiability class C^0 .
9. The method of claim 8, wherein the resulting concatenated segment is of differentiability class C^n , where $n = 1 \dots 6$.
10. The method of one of the preceding claims, wherein the optical element is controlled by a feedback control and/or by a feedforward control concerning the parameter.
30
11. The method of one of the preceding claims, wherein the at least one point of the optical element is a point of interest of the optical element.

12. A microlithographic projection exposure apparatus comprising an optical element, at least one actuator configured to move and/or deform the optical element in at least one degree of freedom and a control device, wherein the control device is adapted to perform at least one of the preceding methods.
- 5 13. The apparatus of claim 12, wherein the optical element is a mirror having a mirror substrate and a reflection region formed on a surface of the mirror substrate.

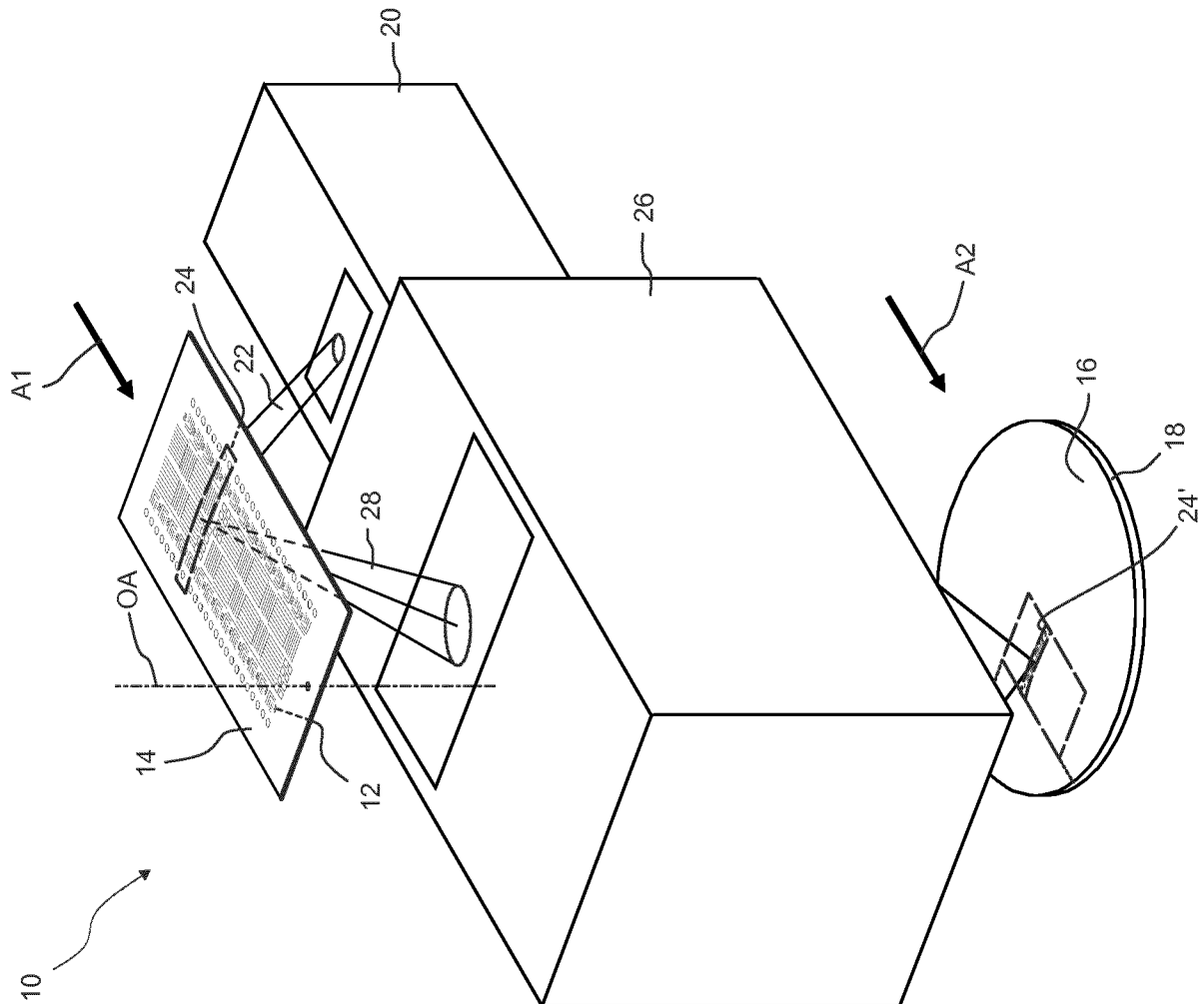


Fig. 1

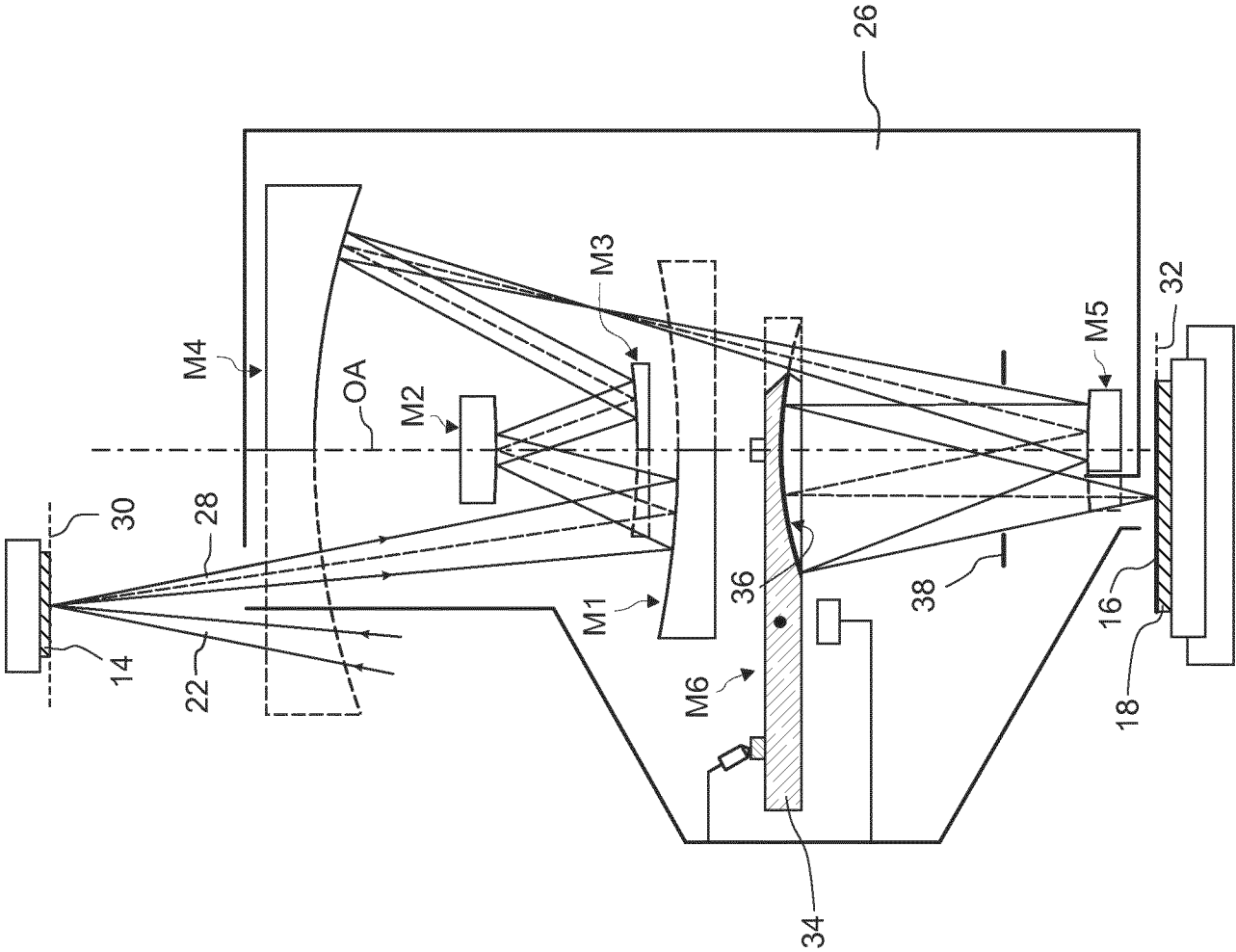


Fig. 2

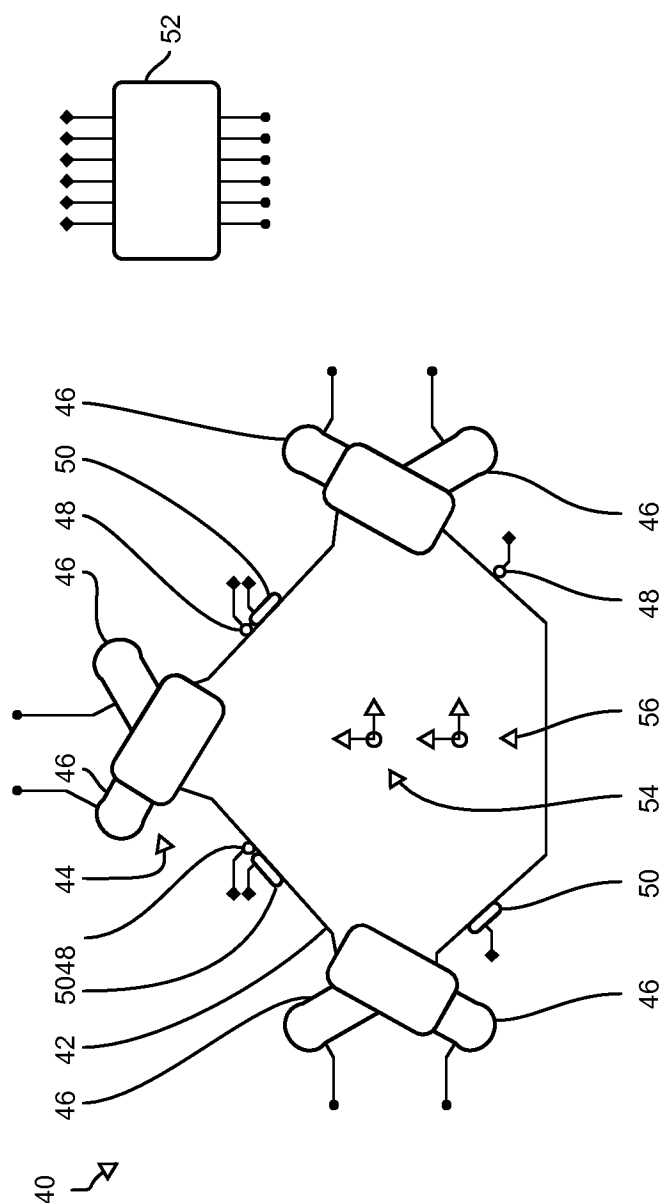


Fig. 3

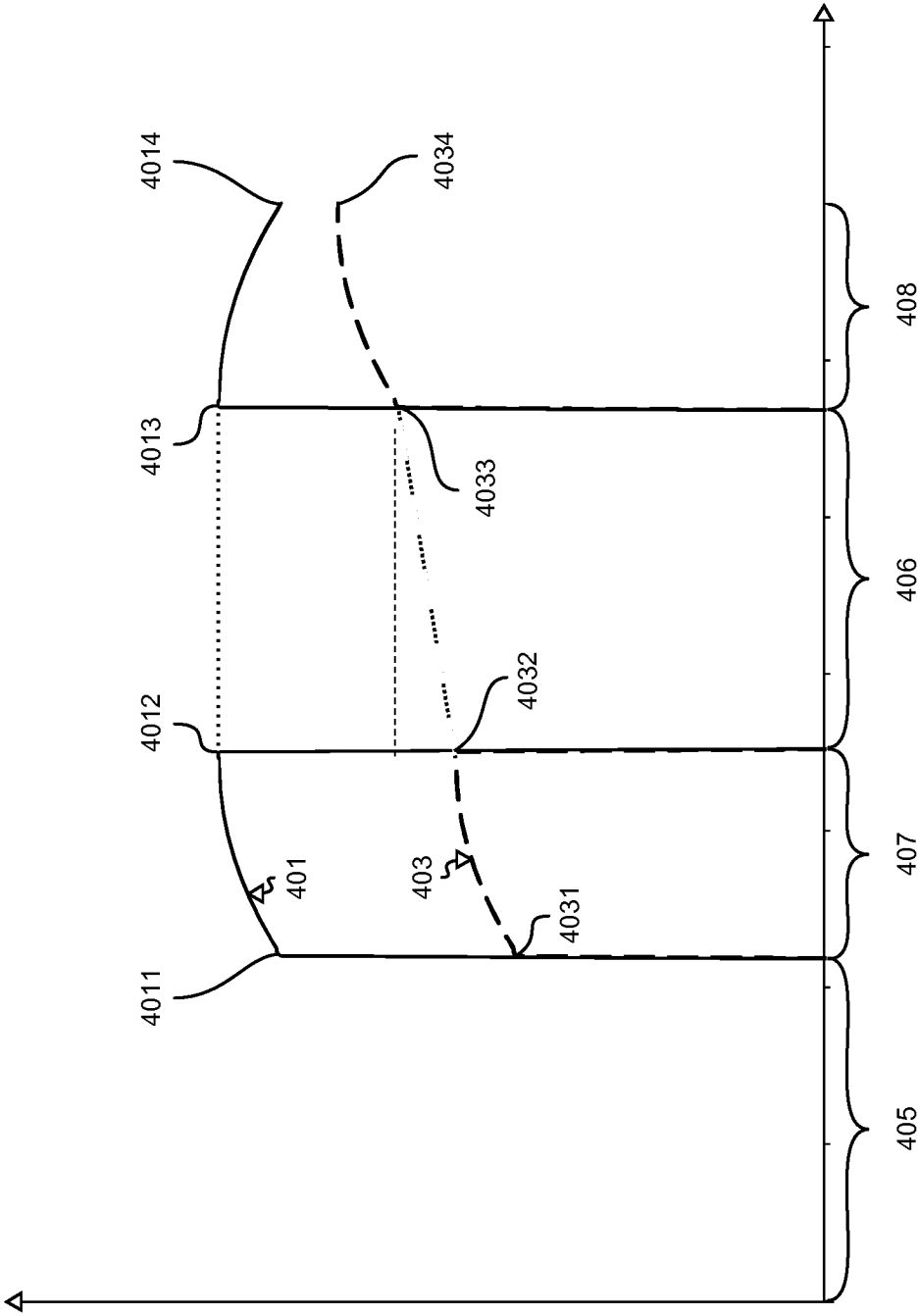


Fig. 4

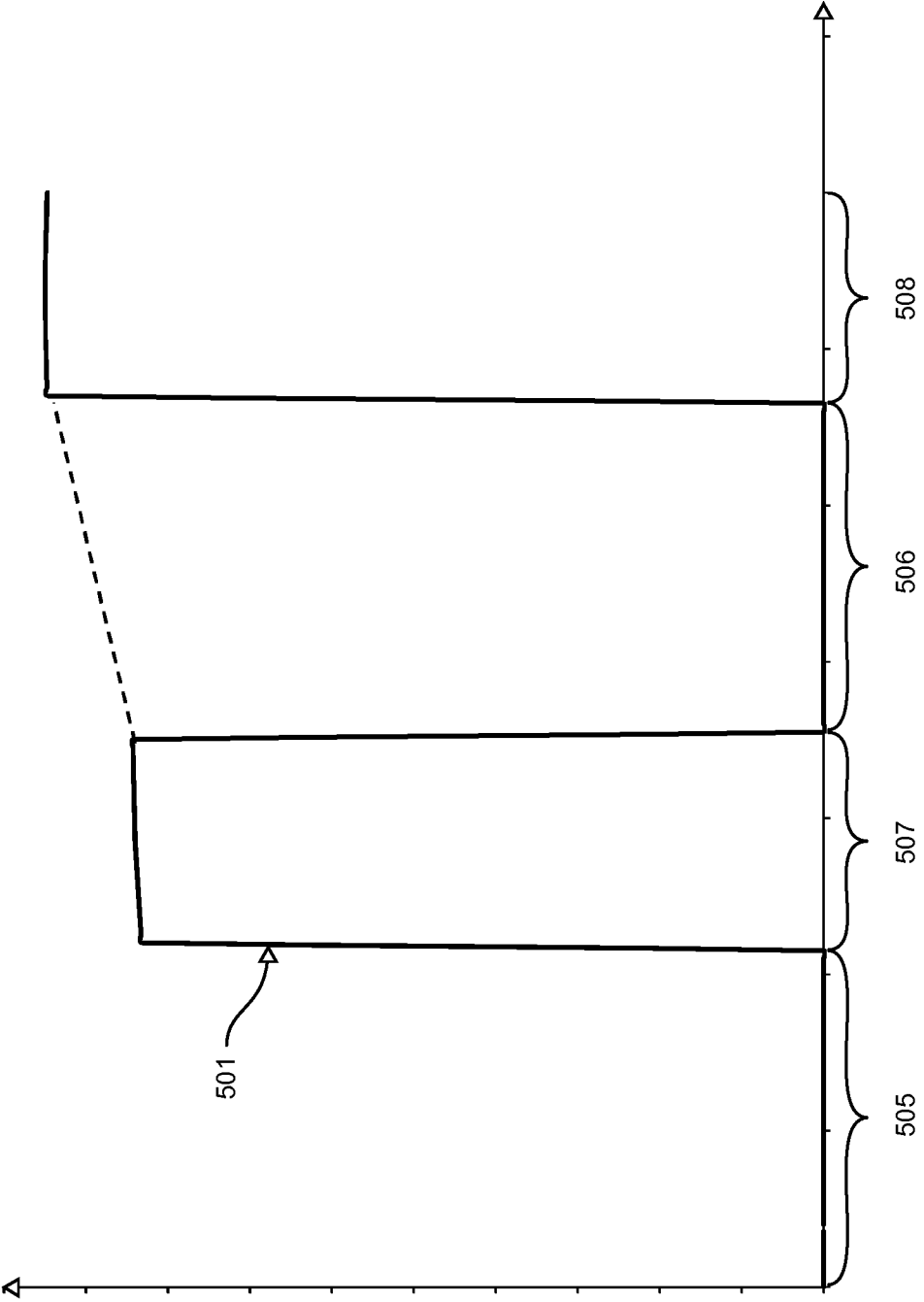


Fig. 5

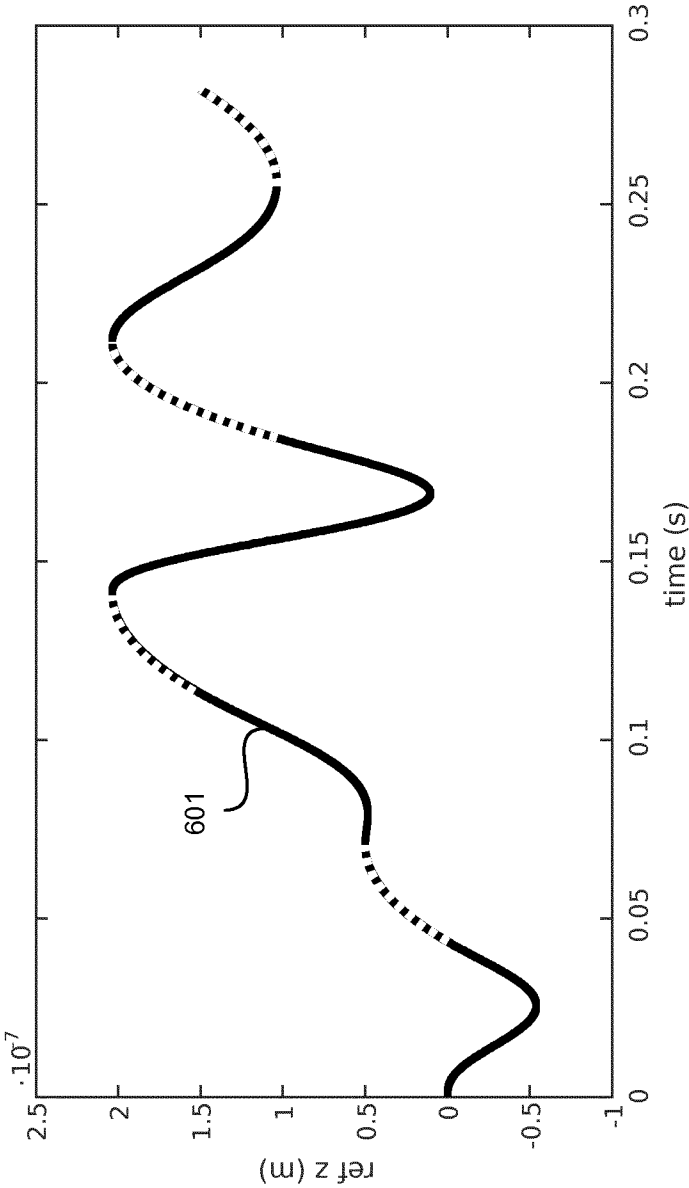


Fig. 6

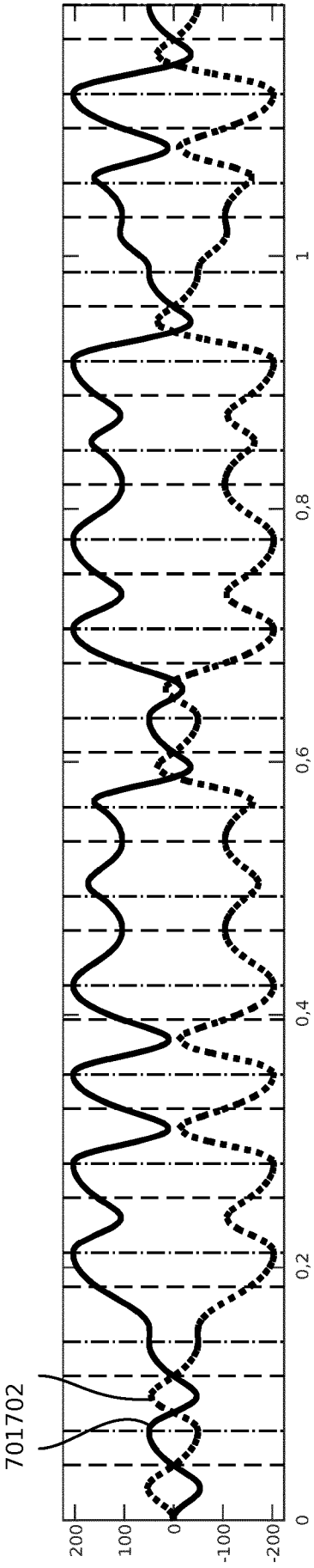


Fig. 7

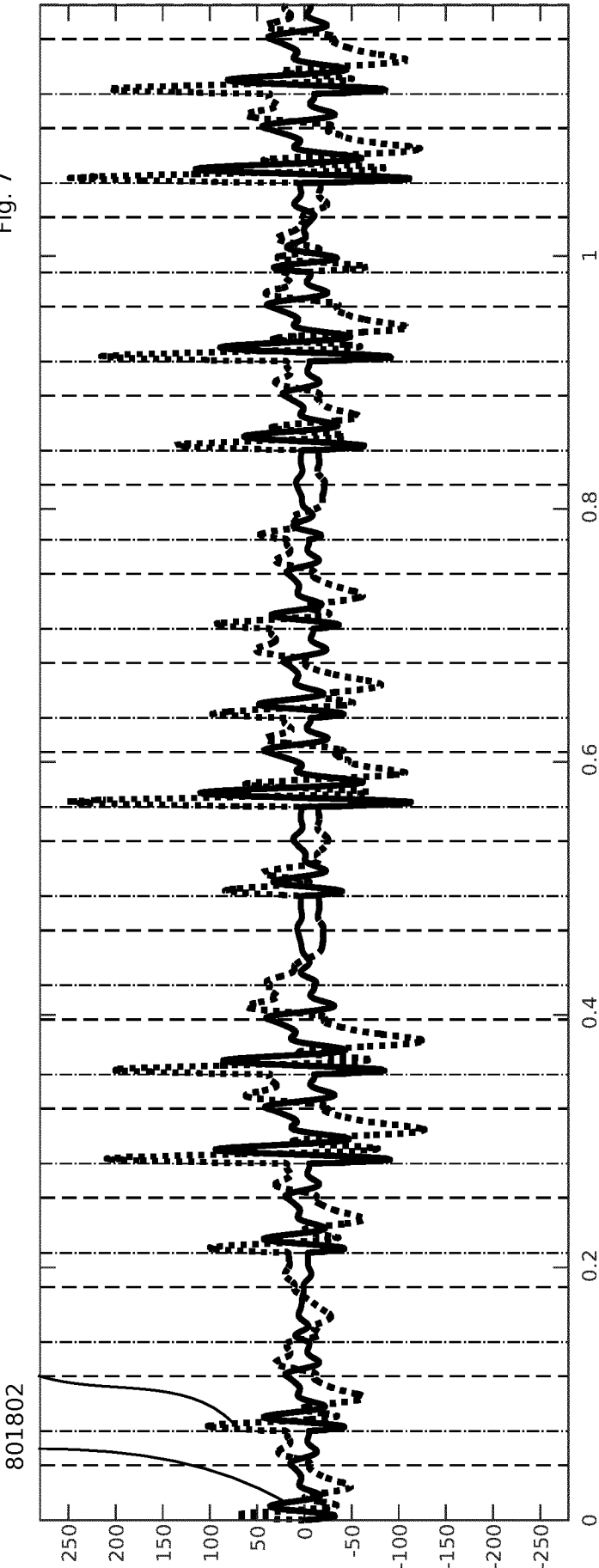


Fig. 8

INTERNATIONAL SEARCH REPORT

International application No

PCT/EP2017/084276

A. CLASSIFICATION OF SUBJECT MATTER
 INV. G03F7/20
 ADD.

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
 G03F

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

EPO-Internal, WPI Data, INSPEC

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 2005/128460 A1 (VAN DEN BIGGELAAR PETRUS MARIN [NL] ET AL) 16 June 2005 (2005-06-16) paragraphs [0089] - [0103], [0113]; figures 6, 7	1,3-10, 12,13
X	US 2008/062391 A1 (UCHIDA YOSHINORI [JP] ET AL) 13 March 2008 (2008-03-13) paragraphs [0060] - [0066], [0074]; figure 4 ----- -/--	1-9,11, 12



Further documents are listed in the continuation of Box C.



See patent family annex.

* Special categories of cited documents :

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"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

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"&" document member of the same patent family

Date of the actual completion of the international search

12 April 2018

Date of mailing of the international search report

23/04/2018

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 Fax: (+31-70) 340-3016

Authorized officer

Eisner, Klaus

INTERNATIONAL SEARCH REPORT

International application No

PCT/EP2017/084276

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT		
Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	HAI-HONG PAN ET AL: "The Multi-Motion-Overlap Strategy to Minimize Time between Continuous Exposure Scans for Wafer Stage", ELECTRONIC PACKAGING TECHNOLOGY, 2007. ICEPT 2007. 8TH INTERNATIONAL CONFERENCE ON, IEEE, PI, 14 August 2007 (2007-08-14), pages 1-7, XP031228201, ISBN: 978-1-4244-1391-1 the whole document -----	1-13

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No

PCT/EP2017/084276

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