

**Lithographic Apparatus, Device Manufacturing Method, and  
Device Manufactured Thereby**

The present invention relates to a lithographic projection apparatus comprising:

- at least one moveable object having a mass, in particular a substrate table or a mask table, and
  - 5 - a position control system for controlling a position of said moveable object, the position control system comprising a position controller outputting a position controller force; and a position feedback circuit feeding back a determined actual position of the object to an input of the position controller.
- 10 A lithographic projection apparatus generally comprises one or more objects, which may be moveable, such as a mask table, a substrate table, and the like. Hereinafter, the lithographic projection apparatus including any moveable objects will be described in further detail.

15           The term "patterning means" as hereinafter employed should be broadly interpreted as referring to means that can be used to endow an incoming radiation beam with a patterned cross-section, corresponding to a pattern that is to be created in a target portion of the substrate; the term "light valve" can also be used in this

20 context. Generally, the said pattern will correspond to a particular functional layer in a device being created in the target portion, such as an integrated circuit or other device (see below). Examples of such patterning means include:

- A mask. The concept of a mask is well known in lithography, and
  - 25 it includes mask types such as binary, alternating phase-shift, and attenuated phase-shift, as well as various hybrid mask types.
- Placement of such a mask in the radiation beam causes selective

the case of a reflective mask) of the radiation impinging on the mask, according to the pattern on the mask. In the case of a mask, the support structure will generally be a mask table, which ensures that the mask can be held at a desired position in the incoming radiation beam, and that it can be moved relative to the beam if so desired;

- A programmable mirror array. One example of such a device is a matrix-addressable surface having a viscoelastic control layer and a reflective surface. The basic principle behind such an apparatus is that (for example) addressed areas of the reflective surface reflect incident light as diffracted light, whereas unaddressed areas reflect incident light as undiffracted light. Using an appropriate filter, the said undiffracted light can be filtered out of the reflected beam, leaving only the diffracted light behind; in this manner, the beam becomes patterned according to the addressing pattern of the matrix-addressable surface. An alternative embodiment of a programmable mirror array employs a matrix arrangement of tiny mirrors, each of which can be individually tilted about an axis by applying a suitable localized electric field, or by employing piezoelectric actuation means. Once again, the mirrors are matrix-addressable, such that addressed mirrors will reflect an incoming radiation beam in a different direction than unaddressed mirrors; in this manner, the reflected beam is patterned according to the addressing pattern of the matrix-addressable mirrors. The required matrix addressing can be performed using suitable electronic means. In both of the situations described hereabove, the patterning means can comprise one or more programmable mirror arrays. More information on mirror arrays as here referred to can be gleaned, for example, from United States Patents US 5,296,891 and US 5,523,193, and PCT patent applications WO 98/38597 and WO 98/33096, which are incorporated herein by reference. In the case of a programmable

mirror array, the said support structure may be embodied as a frame or table, for example, which may be fixed or movable as required; and

- A programmable LCD array. An example of such a construction is given in United States Patent US 5,229,872, which is incorporated  
5 herein by reference. As above, the support structure in this case may be embodied as a frame or table, for example, which may be fixed or movable as required.

For purposes of simplicity, the rest of this text may, at certain locations, specifically direct itself to examples involving a  
10 mask and mask table; however, the general principles discussed in such instances should be seen in the broader context of the patterning means as hereabove set forth.

Lithographic projection apparatus can be used, for example, in the manufacture of integrated circuits (ICs). In such a  
15 case, the patterning means may generate a circuit pattern corresponding to an individual layer of the IC, and this pattern can be imaged onto a target portion (e.g. comprising one or more dies) on a substrate (silicon wafer) that has been coated with a layer of radiation-sensitive material (resist). In general, a single wafer  
20 will contain a whole network of adjacent target portions that are successively irradiated via the projection system, one at a time. In current apparatus, employing patterning by a mask on a mask table, a distinction can be made between two different types of machine. In one type of lithographic projection apparatus, each target portion is  
25 irradiated by exposing the entire mask pattern onto the target portion in one go; such an apparatus is commonly referred to as a wafer stepper or step-and-repeat apparatus. In an alternative apparatus – commonly referred to as a step-and-scan apparatus – each target portion is irradiated by progressively scanning the mask  
30 pattern under the projection beam in a given reference direction (the "scanning" direction) while synchronously scanning the substrate

table parallel or anti-parallel to this direction; since, in general, the projection system will have a magnification factor  $M$  (generally  $< 1$ ), the speed  $V$  at which the substrate table is scanned will be a factor  $M$  times that at which the mask table is scanned. More  
5 information with regard to lithographic devices as here described can be gleaned, for example, from US 6,046,792, incorporated herein by reference.

In a manufacturing process using a lithographic projection apparatus, a pattern (e.g. in a mask) is imaged onto a substrate that  
10 is at least partially covered by a layer of radiation-sensitive material (resist). Prior to this imaging step, the substrate may undergo various procedures, such as priming, resist coating and a soft bake. After exposure, the substrate may be subjected to other procedures, such as a post-exposure bake (PEB), development, a hard  
15 bake and measurement/inspection of the imaged features. This array of procedures is used as a basis to pattern an individual layer of a device, e.g. an IC. Such a patterned layer may then undergo various processes such as etching, ion-implantation (doping), metallization, oxidation, chemo-mechanical polishing, etc., all intended to finish  
20 off an individual layer. If several layers are required, then the whole procedure, or a variant thereof, will have to be repeated for each new layer. Eventually, an array of devices will be present on the substrate (wafer). These devices are then separated from one another by a technique such as dicing or sawing, whence the  
25 individual devices can be mounted on a carrier, connected to pins, etc. Further information regarding such processes can be obtained, for example, from the book "Microchip Fabrication: A Practical Guide to Semiconductor Processing", Third Edition, by Peter van Zant, McGraw Hill Publishing Co., 1997, ISBN 0-07-067250-4, incorporated  
30 herein by reference.

For the sake of simplicity, the projection system may

hereinafter be referred to as the "lens"; however, this term should be broadly interpreted as encompassing various types of projection system, including refractive optics, reflective optics, and catadioptric systems, for example. The radiation system may also  
5 include components operating according to any of these design types for directing, shaping or controlling the projection beam of radiation, and such components may also be referred to below, collectively or singularly, as a "lens". Further, the lithographic apparatus may be of a type having two or more substrate tables  
10 (and/or two or more mask tables). In such "multiple stage" devices the additional tables may be used in parallel, or preparatory steps may be carried out on one or more tables while one or more other tables are being used for exposures. Dual stage lithographic apparatus are described, for example, in US 5,969,441 and  
15 WO 98/40791, both incorporated herein by reference.

The movement of one or more moveable mask tables, one or more moveable substrate tables and other moveable tables, or other moveable objects being part of the lithographic projection apparatus in general, may be controlled by a position control system.  
20 Conventionally, e.g. as disclosed in European Patent No. 1,265,106, a position control system for an object comprises a position controller and a position feedback circuit. A desired position is supplied to the position controller which calculates the required movement of the object. The position controller exerts a position control force on  
25 the object corresponding to the required movement. Via the position feedback circuit the position controller receives information on the actual position of the object. If the determined actual position deviates from the desired position, the position controller may change the position control force until the object reaches the  
30 desired position.

A deviation of the actual position from the calculated

position may result from external forces. In case of a multi-stage lithographic apparatus, air-pressure changes induced by an acceleration of one stage may lead to an external disturbance force on another stage, for example. The sensitivity of the position  
5 control system to external forces should be as small as possible, but other design parameters and requirements limit the possibilities to decrease the sensitivity to external forces.

It is an object of the present invention to decrease the sensitivity of an object position control system to external forces,  
10 in particular - but not limited to - a position control system for moveable objects in a multi-stage lithographic projection apparatus.

It is a further object of the present invention not to influence other design parameters and requirements when implementing measures to decrease the sensitivity of an object position control  
15 system to external forces.

These and other objects are achieved according to the invention in a lithographic projection apparatus as specified above, characterized in that the position control system further comprises an acceleration control system comprising

20 - a first acceleration circuit branch comprising a subtractor into which the position controller force is input; and a first filter having a first gain into which the output of the subtractor is input and outputting a control force which is to be exerted on the object; and

25 - a second acceleration circuit branch comprising a second filter having a second gain and into which an acceleration control signal is input, the output of the second circuit branch being input into said subtractor to subtract the output of the second circuit branch from the position controller force.

30 The lithographic apparatus with one or more position control systems according to the present invention advantageously

employs an acceleration feedback or an acceleration error feedforward via a second acceleration circuit branch. When a force is exerted on an object, the object tends to accelerate. Thus, when an external force is exerted on the object in addition to the position control  
5 force, the object does not accelerate as calculated by the position control system. Using feedback of the acceleration of the object or of the acceleration error, i.e. the difference between the actual acceleration of the object and the intended acceleration, the additional acceleration as a result of the external disturbance force  
10 may be compensated, or at least diminished.

However, an acceleration control system may introduce a gain, which may also influence the position control force. However, by placing at least two filters, the first filter and the second filter, in the acceleration control system, the system according to  
15 the present invention may be advantageously designed such that its characteristics differ for forces input into the system at different input nodes. The influence of the acceleration control system on the position control force may thus be differentiated from the influence of the acceleration control system on the disturbance force.

20 The first filter having a first gain comprised in a first acceleration circuit branch may be located between the position controller and the object. The second filter may be located in an acceleration feedback circuit, e.g. between the output of an object filter, i.e. the actual acceleration, and the input of the first  
25 filter, or in an acceleration feedforward circuit, e.g. having an acceleration error signal as input. In each case, the signal input into the second filter is a signal derived from the actual acceleration and may be regarded as an acceleration control signal. Thus, the position controller force is filtered by the first filter  
30 before it is applied to the object, but after a filtered acceleration signal has been subtracted therefrom by a subtractor. The disturbance

force on the other hand is directly exerted on the object, resulting in a possibly different transfer function of the system for the disturbance force.

Please note that a transfer function of the system for a position controller force is a transfer function from the input of subtractor 8 as input node to the acceleration of the object as the output. A transfer function for a disturbance force is a transfer function from the input of the object filter as input node to the acceleration of the object as the output.

A force exerted on an object results in an acceleration of the object. The amount of acceleration results from the force applied to the object: the force may be considered to be filtered by the object. Thus, in a schematical representation of the system, the object may be (and hereinafter will be) represented as an object filter having an object gain.

An advantage of the position control system employing an acceleration control system according to the present invention is the differentiated transfer functions for a position controller force and an external force. This difference allows for a system design that decreases the influence of an external force with a minimum of influence on any other design parameter or requirements.

Preferably, the acceleration control system has a first transfer function for the position controller force input to the subtractor and a second transfer function for a disturbance force directly exerted on the object, the first transfer function being substantially equal to an object gain and the second transfer function being generally smaller than the object gain, wherein the object gain is substantially equal to an inverse of the mass of the object. With the transfer function of the acceleration control system for the position control force equaling the object gain, the position control system, and in particular the position controller, does not

need to be adapted for the added acceleration control system. Without the acceleration control system, the position controller already experienced the object gain, and thus virtually nothing changed. However, without the acceleration control system, a disturbance force also experienced the object gain, but with the acceleration control system having a second transfer function for the disturbance force smaller than the object gain, the experienced object gain is smaller. Therefore, the object accelerates less due to a disturbance force than without the acceleration control system.

In an embodiment of the present invention, the acceleration control system has a selected loop gain, the first transfer function being

$$G1 = \frac{1}{m},$$

the second transfer function being

$$G2 = \frac{1}{m + Kl},$$

and the loop gain being

$$Kl = Kf \cdot Ks.$$

wherein  $m$  is the mass of the object,  $Kl$  is the loop gain,  $Kf$  is the first gain of the first filter and  $Ks$  is the second gain of the second filter.

In a position control system comprising the acceleration control system having the first and second transfer functions  $G1$  and  $G2$ , the acceleration due to disturbance forces may be decreased to any arbitrarily selected level. The transfer functions  $G1$  and  $G2$  may denote the relation of the acceleration in response to the respective forces (the effected quantities by the transfer functions, thus the output, are object accelerations). The transfer function for the position controller is held constant to the object gain, but the transfer function for a disturbance force may be selected by selecting a loop gain  $Kl$ . Any loop gain  $Kl$  may be selected and

implemented by selecting a corresponding first gain and second gain. However, it should be noted that filter design may impose limitations to the obtainable first gain and second gain, and thus to the obtainable loop gain.

A person skilled in the art will be able to deduce suitable first filter and second filter characteristics from the given transfer functions and loop gain, and to design corresponding filters. However, for completeness, suitable gains are given: a suitable first gain being

$$K_f = 1 + \frac{Kl}{m}, \text{ and}$$

a suitable second gain being

$$K_s = \frac{Kl}{1 + \frac{Kl}{m}}.$$

Advantageously, the first transfer function  $G_1$  does not substantially vary as a function of an input frequency, and the second transfer function  $G_2$  varies as a function of an input frequency. To ensure system stability under all circumstances, the second transfer function for a disturbance force may vary as a function of the frequency of the applied disturbance force. For higher frequencies, the object gain  $H_o$  generally starts deviating from  $1/m$ , for example due to dynamics and/or time delays. To avoid instability, it is therefore advantageous to give  $K_l$  a smaller gain for higher frequencies, because stability is guaranteed if the product of  $K_l$  and  $H_o$  is smaller than 1, irrespective of the phase. The result is that  $G_2$  increases up to  $1/m$  for increasing frequency.

As the above-described system instability may occur in particular at high frequencies, it is advantageous that the the loop gain  $K_l$  decreases with increasing frequency, resulting in a second transfer function  $G_2$  that increases with increasing input frequency. With the increasing transfer function, it may approach the original

object gain. In that case, the acceleration control system may not influence any force above a certain frequency applied to the object.

In an embodiment of the present invention in which the second transfer function  $G_2$  is a function of an input frequency, the loop gain  $K_1$  is provided by a frequency dependent loop filter  $H_l(s)$ ,  
 5 the frequency dependency of the first filter  $H_f$  being

$$H_f(s) = 1 + \frac{H_l(s)}{m},$$

and the frequency dependency of the second filter  $H_s(s)$  being

10

$$H_s(s) = \frac{H_l(s)}{1 + \frac{H_l(s)}{m}}.$$

To obtain a frequency dependent second transfer function  $G_2$ , the loop gain  $K_1$  may be a function of a frequency, i.e. a loop filter  $H_l(s)$ . Consequently, the first filter and the second filter may become functions of the frequency, as the first filter and the  
 15 second filter may be constructed using said loop filter. A suitable loop filter is a second-order low-pass filter or an integrator.

It should be noted, that despite the frequency dependency of the first filter and the second filter, the first transfer function is still substantially equal to the inverse of the mass of  
 20 the object, and therefore independent from any frequency.

In an embodiment of the present invention, the position control system is a discrete time system. Such a digital system is easily designed and cost-effective.

In a further embodiment, the position control system has  
 25 at least a process transfer function delay  $D_p = z^{-p}$  in series with the object gain and an acceleration measurement delay  $D_a = z^{-q}$  in the acceleration feedback circuit in series with the second gain. The position control system may exhibit delays anywhere in the system, as stated above. The delays may be measured, calculated or otherwise

deduced and thereafter modeled and included in the system design.

Two important delays that may be present in the system are a process transfer function delay  $D_p$  and an acceleration measurement delay  $D_a$ . The process transfer function delay  $D_p$  represents an overall delay that occurs between the moment the position controller outputs a position controller force and the moment the object accelerates due to that position controller force. The acceleration measurement delay  $D_a$  represents any delay that occurs during the measurement of the acceleration of the object.

In a digital system, the two delays  $D_p$  and  $D_a$  may be represented as  $D_p = z^{-p}$  and  $D_a = z^{-q}$  and introduced in the system design. In this representation,  $p$  and  $q$  are not limited to integer numbers. Introducing these two delays in the digital system design leads to a suitable first filter being:

$$H_f(z) = 1 + H_l(z) \frac{z^{-(p+q)}}{m},$$

and a suitable second filter being:

$$H_s(z) = \frac{H_l(z)}{1 + H_l(z) \frac{z^{-(p+q)}}{m}}.$$

Although the delay filters are presented and described in combination with a digital position control system, it should be understood that the delay filters may analogously be comprised in an analogue position control system as disclosed hereinabove.

While any filter has been described by its characteristics, formulated in equations, it is noted that the person skilled in the art will be able to implement the filters using the given description and formulas in a position control system according to the present invention.

In a further aspect of the present invention there is provided a position control system as above described in relation to a lithographic apparatus.

According to a another aspect of the present invention, there is provided a device manufacturing method comprising a step of controlling a position of at least one moveable object, in particular said substrate, said patterning means, or both; wherein the step of  
5 controlling a position comprises the steps of:

- exerting a control force ( $F_c$ ) on said moveable object;
- determining an actual position of said moveable object;
- feeding back said position to an input of a position

controller (6),

10 characterized by

- subtracting a filtered acceleration control signal from a position controller force ( $F_p$ ) using a subtractor (8) comprised in a first acceleration circuit branch;
- filtering the output of the subtractor (8) using a first  
15 filter ( $H_f$ ) having a first gain ( $K_f$ ) comprised in the first acceleration circuit branch;
- determining an acceleration of said moveable object;
- filtering an acceleration control signal using a second filter ( $H_s$ ) having a second gain ( $K_s$ ) comprised in a  
20 second acceleration circuit branch; and
- supplying the output of the second acceleration circuit branch to the subtractor (8) comprised in the first acceleration circuit branch.

Although specific reference may be made in this text to  
25 the use of the apparatus according to the invention in the manufacture of ICs, it should be explicitly understood that such an apparatus has many other possible applications. For example, it may be employed in the manufacture of integrated optical systems, guidance and detection patterns for magnetic domain memories,  
30 liquid-crystal display panels, thin-film magnetic heads, etc. The skilled artisan will appreciate that, in the context of such

alternative applications, any use of the terms "reticle", "wafer" or "die" in this text should be considered as being replaced by the more general terms "mask", "substrate" and "target portion", respectively.

In the present document, the terms "radiation" and "beam" are used to encompass all types of electromagnetic radiation, including ultraviolet (UV) radiation (e.g. with a wavelength of 365, 248, 193, 157 or 126 nm) and extreme ultra-violet (EUV) radiation (e.g. having a wavelength in the range 5-20 nm), as well as particle beams, such as ion beams or electron beams.

Embodiments of the invention will now be described, by way of example only, with reference to the accompanying schematic drawings in which corresponding reference symbols indicate corresponding parts, and in which:

Figure 1 depicts a lithographic projection apparatus according to an embodiment of the invention;

Figure 2 is a schematic block diagram of a prior art position control system employing position feedback;

Figure 3 is a schematic block diagram of an embodiment of a position control system according to the present invention;

Figure 4A is a schematic block diagram of a conventional acceleration control system;

Figure 4B is a schematic block diagram of an acceleration control system according to the present invention having a position controller force as an input;

Figure 4C is a schematic block diagram of an acceleration control system according to the present invention having a disturbance force as an input;

Figure 5A is a schematic block diagram of an embodiment of a first filter;

Figure 5B is a schematic block diagram of an embodiment of a second filter;

Figure 5C is a schematic block diagram of an embodiment of a position control system according to the present invention;

Figure 6 is a schematic block diagram of a digital embodiment of the present invention, wherein some filters represent possibly in the system present delays.

Figure 7A and 7B are graphs illustrating the process sensitivity achieved with the digital embodiment of Fig. 6.

Figure 8 is a schematic block diagram of a further embodiment of the present invention employing acceleration setpoint feedforward.

#### Embodiment 1

Figure 1 schematically depicts a lithographic projection apparatus 1 according to a particular embodiment of the invention.

The apparatus comprises:

- a radiation system IL, for supplying a projection beam PB of radiation. In this particular case, the radiation system also comprises a radiation source LA;
- a first object table (mask table) MT provided with a mask holder for holding a mask MA (e.g. a reticle), and connected to first positioning means PM for accurately positioning the mask with respect to item PL;
- a second object table (substrate table) WT provided with a substrate holder for holding a substrate W (e.g. a resist-coated silicon wafer), and connected to second positioning means PW for accurately positioning the substrate with respect to item PL; and
- a projection system ("lens") PL for imaging an irradiated portion of the mask MA onto a target portion C (e.g. comprising one or more dies) of the substrate W.

As here depicted, the apparatus is of a transmissive type (i.e. has a transmissive mask). However, in general, it may also be

of a reflective type, for example (with a reflective mask).

Alternatively, the apparatus may employ another kind of patterning means, such as a programmable mirror array of a type as referred to above.

5           The source LA produces a beam of radiation. This beam is fed into an illumination system (illuminator) IL, either directly or after having traversed conditioning means, such as a beam expander, for example. The illuminator IL may comprise adjusting means for setting the outer and/or inner radial extent (commonly referred to as  
10  $\sigma$ -outer and  $\sigma$ -inner, respectively) of the intensity distribution in the beam. In addition, it will generally comprise various other components, such as an integrator and a condenser. In this way, the beam PB impinging on the mask MA has a desired uniformity and intensity distribution in its cross-section.

15           It should be noted with regard to figure 1 that the source LA may be within the housing of the lithographic projection apparatus (as is often the case when the source LA is a mercury lamp, for example), but that it may also be remote from the lithographic projection apparatus, the radiation beam which it produces being led  
20 into the apparatus (e.g. with the aid of suitable directing mirrors); this latter scenario is often the case when the source LA is an excimer laser. The current invention and claims encompass both of these scenarios.

          The beam PB subsequently intercepts the mask MA, which is  
25 held on a mask table MT. Having traversed the mask MA, the beam PB passes through the lens PL, which focuses the beam PB onto a target portion C of the substrate W. With the aid of the second positioning means PW (and interferometric measuring means IF), the substrate table WT can be moved accurately, e.g. so as to position different  
30 target portions C in the path of the beam PB. Similarly, the first positioning means PM can be used to accurately position the mask MA

with respect to the path of the beam PB, e.g. after mechanical retrieval of the mask MA from a mask library, or during a scan. In general, movement of the object tables MT, WT will be realized with the aid of a long-stroke module (coarse positioning) and a short-stroke module (fine positioning), which are not explicitly depicted in figure 1. However, in the case of a wafer stepper (as opposed to a step-and-scan apparatus) the mask table MT may just be connected to a short stroke actuator, or may be fixed. Mask MA and substrate W may be aligned using mask alignment marks M1, M2 and substrate alignment marks P1, P2.

The depicted apparatus can be used in two different modes:

1. In step mode, the mask table MT is kept essentially stationary, and an entire mask image is projected in one go (i.e. a single "flash") onto a target portion C. The substrate table WT is then shifted in the x and/or y directions so that a different target portion C can be irradiated by the beam PB; and

2. In scan mode, essentially the same scenario applies, except that a given target portion C is not exposed in a single "flash". Instead, the mask table MT is movable in a given direction (the so-called "scan direction", e.g. the y direction) with a speed  $v$ , so that the projection beam PB is caused to scan over a mask image; concurrently, the substrate table WT is simultaneously moved in the same or opposite direction at a speed  $V = Mv$ , in which  $M$  is the magnification of the lens PL (typically,  $M = 1/4$  or  $1/5$ ). In this manner, a relatively large target portion C can be exposed, without having to compromise on resolution.

The positioning means PM and PW may be embodiments of the position control system according to the present invention. The figures and their description hereinafter will be dedicated to such position control systems. First, for a good understanding, the construction and operation of a position control system will be

described in relation to a prior art position control system.

Thereafter, an embodiment of the present invention will be presented and described.

Figure 2 shows a prior art embodiment of a position  
5 control system that employs position feedback for controlling the  
position of an object. Externally from the position control system, a  
desired absolute position is determined and fed to the position  
control system via a set point input 2. From the desired absolute  
position, a measured actual absolute position of the controlled  
10 object may be subtracted resulting in a desired relative movement  
signal 4 of the object. The desired relative movement signal 4 is  
then supplied to a position controller 6 via a position controller  
input. The position controller 6 is a device well known to a person  
skilled in the art and capable of translating a movement signal into  
15 control signals. The position controller 6 may comprise a PID  
controller, a low-pass filter and an amplifier, for example.

The control signal output from the position controller 6  
may be referenced as a position controller force  $F_p$ , since the  
control signal acts upon the object as a force. The position  
20 controller force  $F_p$  results in an acceleration of the object  
depending on a mass  $m$  of the object, which is represented in the  
diagram as object filter  $H_o$ , having an object gain  $K_o$ . Apart from the  
mass  $m$  of the object, also other parameters, such as friction, may be  
present and represented by the object gain  $K_o$ , however, for  
25 simplicity, it is assumed that the object gain  $K_o$  only depends on the  
mass of the object.

Due to physical laws, a velocity of the object equals the  
acceleration of the object integrated over time, depicted by means of  
integrator 14. Similarly, an integration of a velocity signal 16 by  
30 an integrator 18 leads to a determined actual position signal 20. The  
position signal 20 is fed back to the input of the position control

system via a position feedback circuit 22.

Not only the force  $F_p$  output by the position controller, but also other forces may be exerted on the object. In case of a multistage lithographic apparatus, the object may be one stage. Air pressure changes induced by another stage may apply an external disturbance force on said stage. However, any external force disturbs the position control system as it results in an unexpected displacement of the object.

A disturbance force  $F_d$  is indicated in Figure 2 by a dotted arrow, as it is not a physical component of the system. It is however included in Figure 2 to show where the disturbance force  $F_d$  is to be considered to be input in the system as this is an important aspect for understanding the present invention.

A person skilled in the art will readily understand how the position control system of Fig. 2 generally functions. A position input at set point 2 is subtracted with a determined, i.e. calculated or measured, actual position signal 20 by a subtractor resulting in a desired movement signal 4. Based upon the desired movement 4, the position controller 6 determines the force to move the object to the desired position. The force  $F_p$  output from the position controller 6 is applied to the object. Further, the disturbance force  $F_d$ , which is assumed to be present in this case, is also applied to the object. The object accelerates as a result of the force resulting from the force  $F_p$  applied by the position controller 6, and by the disturbance force  $F_d$ , depending on the mass of the object represented by object filter  $H_o$  having object gain  $K_o$  equaling  $1/m$ ,  $m$  being the mass of the object.

By nature, the actual position signal 20 equals the double integrated acceleration signal 12. Schematically, this double integration is performed by integrators 14 and 18. If the acceleration signal 12 is desired to be known, it could be measured

directly or derived from the position signal 20 by a double differentiation with respect to time. The determined actual position signal 20 is fed back to the subtractor. The desired movement signal 4 results. The actual movement may however be  
5 different from the desired movement that was intended to result from the force applied by the position controller 6 because of the disturbance force  $F_d$ . Thus, the position controller 6 needs to change the position controller force  $F_p$  to compensate for the disturbance force  $F_d$ .

10           Note that Figure 2 does not include any feedforward circuits. However, in practice, feedforward circuits may be present. For example, the desired position 2 may correspond to a desired object acceleration. The desired object acceleration is generally processed, for example multiplied by the object mass, and added to  
15 the position controller force  $F_p$ . Other feedforward circuits may be present as well, depending on details of object characteristics.

Figure 3 is a diagram of a position control system employing position feedback and acceleration feedback according to the present invention. The diagram comprises an acceleration control  
20 system 34. The acceleration control system 34 comprises a first and a second acceleration circuit branch. The first circuit branch comprises a subtractor 8 and a first filter  $H_f$  having a first gain  $K_f$ . The second circuit branch comprises a second filter  $H_s$  having a second gain  $K_s$ . Further, an acceleration feedback signal 28 is input  
25 to the second filter  $H_s$  and the filtered acceleration feedback signal 32 is output from the second filter  $H_s$  and subtracted from the position controller force  $F_p$  output from the position controller 6 by subtractor 8. Not the position controller force  $F_p$ , but a control force  $F_c$  is exerted on the object. The control force  $F_c$  is output by  
30 the first filter  $H_f$ .

For a good understanding of the acceleration control

system 34, reference is made to Figures 4A, 4B and 4C before describing the functioning of the position control system according to Figure 3.

Figure 4A shows a general basic concept of an acceleration control system 36 comprising a loop gain  $K_l$  and the object filter  $H_o$ . Compared to the system illustrated in Figure 2, the loop gain  $K_l$  and a feedback circuit 38 are added. The acceleration is related to the position controller force  $F_p$  by a gain  $K_l/(m+K_l)$ . The acceleration is related to the disturbance force  $F_d$  by a gain  $1/(m+K_l)$ . Thus, a position controller force  $F_p$  results in a different acceleration compared to a system without the acceleration control system 36. In particular, when  $K_l$  is made frequency dependent so as to diminish the loop gain  $K_l$  for higher frequencies in view of delays or dynamics in  $H_o$ , the relation between position controller force  $F_p$  and the actual acceleration also becomes dependent on the frequency. Thus, the original object gain of  $1/m$  is replaced by a frequency dependent gain. It is difficult for the position controller 6 to compensate this frequency dependent gain. The position controller 6 needs to be modified for this purpose, which is generally very difficult with regard to stability of the position control loop.

Figures 4B and 4C illustrate the acceleration control system 34 according to the present invention having a subtractor 8, a first filter  $H_f$  having a first gain  $K_f$  and a second filter  $H_s$  having a second gain  $H_s$ . Figure 4B illustrates the acceleration control system 34 with only the position controller force  $F_p$  as an input. Figure 4C illustrates the same but only having the disturbance force  $F_d$  as an input. Both acceleration control systems of Figs. 4B and 4C have the actual acceleration of the object as output.

The acceleration resulting from position controller force  $F_p$  should not be changed, i.e. increased or attenuated, by the acceleration control system 34, compared to the acceleration

resulting from position controller force  $F_p$  in the system illustrated in Figure 2. Thus, the gain of the acceleration control system 34 should equal  $1/m$  for a position control force  $F_p$  input to the subtractor 8.

5                   The gain of the acceleration control system 34 equals for an input into the subtractor 8

$$K = \frac{\frac{K_f}{m}}{1 + \frac{K_f \cdot K_b}{m}},$$

and as stated above should equal  $1/m$ . Thus, a first constraint for the first gain  $K_f$  and second gain  $K_s$  is:

10                   
$$\frac{\frac{K_f}{m}}{1 + \frac{K_f \cdot K_s}{m}} = \frac{1}{m}.$$

Now referring to Figure 4C, the disturbance force  $F_d$  should be attenuated with a loop gain  $K_l$  comparable to the loop gain introduced in Figure 4A. In fact, the acceleration control system 34 illustrated in Figure 4C is substantially identical to the circuit in Figure 4A as, in this case, the first filter  $H_f$  and the second filter  $H_s$  may be combined and represented as one filter. Thus, the loop gain  $K_l$  may represent both filters and thus equal the first gain  $K_f$  multiplied by the second gain  $K_s$ :

$$K_l = K_f \cdot K_s,$$

20                   resulting in a second constraint for the first gain  $K_f$  and the second gain  $K_s$ .

It is to be noted that employing an acceleration control system 34 according to the present invention results in an attenuation of an acceleration caused by a disturbance force  $F_d$ , whereas an acceleration caused by the position controller force is kept unchanged.

The two constraints described in relation to Figs. 4B and

4C may be combined to obtain two expressions expressing the desired first gain  $K_f$  for the first filter  $H_f$  and the second gain  $K_s$  for the second filter  $H_s$ :

$$K_f = 1 + \frac{Kl}{m};$$

$$K_s = \frac{Kl}{1 + \frac{Kl}{m}} = \frac{Kl}{K_f}.$$

Figure 5A illustrates an embodiment of a filter having the filter characteristics as formulated for the first filter  $H_f$  above. The filter comprises a first filter  $H_{f1}$  identical to the object filter  $H_o$  with respect to its characteristics and a second filter  $H_{f2}$  corresponding to the loop filter  $H_l$  both put in a feed forward branch.

Figure 5B illustrates an embodiment of a filter having the filter characteristics as formulated for the second filter  $H_s$  above. The filter comprises a first filter  $H_{s1}$  identical to the object filter  $H_o$  with respect to its characteristics and a second filter  $H_{s2}$  corresponding to the loop filter  $H_l$ . The first filter  $H_{s1}$  is placed in a feedback circuit branch.

The physical embodiment of the filters  $H_{f1}$  and  $H_{s1}$ , which are identical to the object filter  $H_o$  with respect to their characteristics, may be a computer implementation. That means that the illustrated filters are implemented in a signal processing device, a programmed computer device for example, which receives the input signal, filters the signal according to the implemented characteristics of the filter (in this case identical to the characteristics of the object filter), and outputs the result. In addition, also other parts of the system may be physically implemented in a well-known computer device or be implemented using any other kind of signal processor.

Figure 5C illustrates an embodiment of a position control

system according to the present invention, wherein the filters introduced in relation to Figs. 5A and 5B are implemented in the position control system employing acceleration feedback illustrated in Fig. 3. In Fig. 5C, a desired position signal is input to the system at set point 2. From the desired position the actual position signal 20 is subtracted resulting in a desired movement signal 4, which is input to a position controller 6. From the position controller force  $F_p$ , a filtered actual acceleration signal 32 is subtracted and input to the first filter  $H_f$ . Now, the output of the first filter  $H_f$  is the control force  $F_c$  applied to the object, represented as the object filter  $H_o$ . The actual acceleration is supplied to the second filter  $H_s$  and the output thereof is subtracted from the position controller force  $F_p$  as described above. From the actual acceleration signal 12, the actual position signal 20 may be calculated and supplied to the system input node, i.e. set point 2, to be subtracted from the input desired position. Again as stated above, usually, the position signal 20 is measured, and the actual acceleration may be determined there from.

In the illustrated position control system, any unexpected acceleration of the object because of a disturbance force  $F_d$  exerted on the object is compensated in an early stage by the acceleration feedback system 34.

It is to be noted, that in the position control system, there is still an unspecified filter present. The loop filter  $H_l$  has at this point not been specified. The acceleration control system is designed such, that the loop filter  $H_l$  only has an impact on a disturbance force  $F_d$  and does not influence the reaction to any position controller force  $F_p$ . Therefore, the loop filter  $H_l$  may be designed according to any suitable filter characteristics.

In an embodiment of the present invention, the loop filter  $H_l$  is designed as a frequency dependent filter, suppressing any low-

frequency disturbance force  $F_d$ , but leaving any high-frequency disturbance force unchanged. In such an embodiment, the loop filter  $H_l$  may be a second-order low-pass filter or an integrator. However, the loop filter  $H_l$  may be frequency independent and thus being just a  
 5 constant gain.

Figure 6 illustrates another embodiment of the present invention. The present invention is embodied as a digital discrete time system. However, as may be in the above-described systems, there may be delays present in the system. Therefore, in Fig. 6, two  
 10 possible delays are included in the position control system. A first delay present in the system may be a process transfer function delay, i.e. a delay from position controller output to actual acceleration of the object. A second delay may be an acceleration measurement delay.

15 The process transfer function delay is introduced in the position control system by amending the object filter  $H_o$  to include the delay. In discrete time, a delay is represented as  $z^{-p}$ , thus the object filter  $H_o$  becoming  $z^{-p}/m$ . The acceleration measurement delay is introduced as a separate delay filter located in the feedback  
 20 branch of the acceleration control system 34.

An acceleration measurement delay filter  $D_a$  equals  $z^{-q}$ . The amended and the added filter lead to amended characteristics of the overall position control system. In particular, the first gain  $G_1$  now changes to  $z^{-p}/m$ , i.e. remaining the same as the object gain  
 25 including delay. However, basically the digital position control system comprising filters representing one or more delays functions similar to the position control system of Figs. 3, 4A - 4C and 5A - 5C. Therefore, a more detailed description of the digital position control system is omitted.

30 Fig. 7A illustrates theoretical and Fig. 7B illustrates practical results achieved with the embodiment described in relation

to Fig. 6. The graphs in Figs. 7A and 7B show the process sensitivity of the digital embodiment as a function of the frequency of the input disturbance force. The frequency on the horizontal axis has a logarithmic scale. The process sensitivity shown in Figs. 7A and 7B is the position loop process sensitivity, i.e. the transfer function from a disturbance force  $F_d$  to the measured position error  $\epsilon$ .

Fig. 7A shows the theoretical process sensitivity, both without and with acceleration feedback according to the present invention. Thus, the theoretical process sensitivity of a digital prior art position control system is shown with a dashed line 52. The theoretical process sensitivity of a position control system according to the present invention is shown with a continuous line 54. In practice, higher-order dynamics are present in the system. The resonance peak near 1 kHz results from such higher-order dynamics. These higher-order dynamics are included in the theoretical model used to calculate these theoretical results.

The process sensitivity of the system according to the present invention is clearly reduced with respect to the process sensitivity of the prior art system, especially for low frequencies. For a 10 Hz disturbance force, the process sensitivity is reduced with about 20 dB (a factor of 10). For frequencies higher than 200 Hz, but lower than 1 kHz, the process sensitivity is slightly increased, and for frequencies higher than 1 kHz, the process sensitivity is substantially the same as for a prior art system.

Fig. 7B shows a dashed line 56 for a prior art system and a continuous line 58 for a system according to the present invention. The graphs represent measured data and thus represent the actual position loop process sensitivity of the system. The process sensitivity of both the prior art system and the system according to the present invention do not substantially differ from the predicted theoretical process sensitivity illustrated in Fig. 7A. Note that

above 1 kHz, measurement noise accounts for non-accuracy in the measurements, which can therefore not sensibly be compared with the theoretical results. Thus, the system according to the present invention functions as may be expected.

5            Fig. 8 illustrates another embodiment of the present invention. Again, a position controller 6 reacts on the difference between the position set point 2 and an actual position signal 20, similar to the first embodiment. In addition to the position controller force  $F_p$ , an acceleration set point feedforward  $A_{ff}$  is  
10 present. The acceleration set point feedforward signal  $A_{ff}$  is generated by a set point acceleration filter  $H_a$ , which has an input that equals the desired acceleration or set point acceleration  $A_{sp}$ . Generally, the set point acceleration filter  $H_a$  includes an inverse of the object gain, in its simplest form equaling  $m$ , the object mass.  
15 Generally, the set point acceleration  $A_{sp}$  substantially equals a double derivative with respect to time of the set point position, input at set point 2. The main goal of the set point acceleration feedforward is to accelerate the object such that its position matches the desired position without needing a mismatch between the  
20 desired and the actual position to make the position controller 6 react. Hence, the acceleration feedforward makes it possible for the object to closely follow its set point position without needing an input to the position controller 6.

          It is observed that the acceleration set point feedforward  
25 signal  $A_{ff}$  enters the system at a node that is comparable to the disturbance force  $F_d$ , as it is directly input into the object filter  $H_o$ . In the embodiment illustrated in Fig. 3, the acceleration control system 34 will attempt to diminish an effect of the acceleration set point feedforward signal  $A_{ff}$ . Obviously, the effect of the  
30 acceleration set point feedforward signal  $A_{ff}$  should not be diminished.

Alternatively, the acceleration set point feedforward signal  $A_{ff}$  could be added to the position controller force  $F_p$ . In that case, the acceleration control system 34 will not attempt to decrease the effect of the acceleration set point feedforward signal  $A_{ff}$ . However, because the acceleration set point feedforward signal  $A_{ff}$  now has to pass through the acceleration control system 34 which has more complicated dynamic characteristics than the object filter  $H_o$  itself, the set point acceleration filter  $H_a$  should be more complex. For that reason, it is advantageous to let the acceleration set point feedforward signal  $A_{ff}$  act directly on the object, as indicated in Fig. 8.

The problem that the acceleration control system 34 reacts on the acceleration caused by the acceleration feedforward may be solved by not feeding back the actual acceleration 12 through second filter  $H_s$ , but feeding an acceleration error signal 44 through second filter  $H_s$ . In such a case, only the acceleration not resulting from the acceleration set point feedforward signal  $A_{ff}$  is fed back into the acceleration control system 34. The acceleration error signal 44 is deduced from the difference between the set point position 2 and the actual position 20 by means of an acceleration error reconstruction filter  $H_r$ , as indicated in Fig. 8. The acceleration error reconstruction filter  $H_r$  generally consists of a double differentiator that differentiates its input twice with respect to time. Because of the sign difference of the output of this reconstruction filter  $H_r$  compared to the original acceleration measurement signal 12, the output of second filter  $H_s$  is added to the position controller force  $F_p$ , instead of being subtracted from it. However, a person skilled in the art will readily understand that an inversion may be performed by a separate inverter to correct the sign difference of the output of the reconstruction filter  $H_r$  and then subtracting the resulting signal using subtractor 8.

Whilst specific embodiments of the invention have been described above, it will be appreciated that the invention may be practiced otherwise than as described. For example, as stated above, the actual position may be measured instead of the acceleration, which will then be calculated from the measured position, or both the acceleration and the position may be measured, allowing to omit any calculation means therefor. Further, specific filter components may be included in  $H_1(s)$  to cope with higher-order effects in the object filter  $H_o$ , such as resonance's.

10           Further, whilst the invention has been described in relation to a lithographic projection apparatus, it should be understood that the present invention may be employed in any system controlling a position of an object. Therefore, the above description is not intended to limit the invention in any way.

CLAIMS

1. Lithographic projection apparatus comprising:

- at least one moveable object having a mass ( $m$ ), in particular a substrate table or a mask table, and
- a position control system for controlling a position of

5 said moveable object, the position control system comprising a position controller (6) outputting a position controller force ( $F_p$ ); and a position feedback circuit (22) feeding back a determined actual position (20) of the object to an input of the position controller (6),

10 characterized in that the position control system further comprises an acceleration control system (34) comprising

- a first acceleration circuit branch comprising a subtractor (8) into which the position controller force ( $F_p$ ) is input; and a first filter ( $H_f$ ) having a first gain ( $K_f$ ) into which the output of the subtractor (8) is input
- 15 and outputting a control force ( $F_c$ ) which is to be exerted on the object; and

20 - a second acceleration circuit branch comprising a second filter ( $H_s$ ) having a second gain ( $K_s$ ) and into which an acceleration control signal is input, the output of the second circuit branch being input into said subtractor (8) to subtract the output of the second circuit branch from the position controller force ( $F_p$ ).

2. Lithographic projection apparatus according to

25 claim 1, wherein the acceleration control system has a first transfer function ( $G_1$ ) for the position control force ( $F_p$ ) input to the subtractor (8) and a second transfer function ( $G_2$ ) for a disturbance force ( $F_d$ ) directly exerted on the object, the first transfer function ( $G_1$ ) being substantially equal to an object gain ( $K_o$ ) and

the second transfer function (G2) being generally smaller than the object gain (Ko), the object gain (Ko) substantially equaling an inverse of the mass of the object (1/m).

3. Lithographic projection apparatus according to  
5 claim 2, wherein the acceleration control system (34) has a selected loop gain (Kl), the first transfer function (G1) being

$$G1 = \frac{1}{m},$$

the second transfer function (G2) being

$$G2 = \frac{1}{m + Kl},$$

10 and the loop gain (Kl) being

$$Kl = Kf \cdot Ks.$$

4. Lithographic projection apparatus according to  
claim 2 or 3, wherein the first transfer function (G1) does not  
substantially vary as a function of an input frequency, and wherein  
15 the second transfer function (G2) varies as a function of an input  
frequency.

5. Lithographic projection apparatus according to  
claim 4, wherein the second transfer function (G2) increases with  
increasing input frequency.

20 6. Lithographic projection apparatus according to  
claim 4 or 5, wherein the loop gain (Kl) is provided by a frequency  
dependent loop filter (Hl(s)), the frequency dependency of the first  
filter (Hf(s)) being

$$Hf(s) = 1 + \frac{Hl(s)}{m},$$

25 and the frequency dependency of the second filter (Hs(s)) being

$$Hs(s) = \frac{Hl(s)}{1 + \frac{Hl(s)}{m}}.$$

7. Lithographic projection apparatus according to  
claim 6, wherein the loop filter (Hl(s)) is a second-order low-pass

filter.

8. Lithographic projection apparatus according to claim 6, wherein the loop filter ( $H_l(s)$ ) is an integrator.

9. Lithographic projection apparatus according to any of the preceding claims, characterized in that the position control system is a discrete time system.

10. Lithographic projection apparatus according to claim 9, comprising one or more delays, in particular a process transfer function delay ( $D_p$ ) equaling  $z^{-p}$  in series with the object, an acceleration measurement delay ( $D_a$ ) equaling  $z^{-q}$  in the second acceleration circuit branch in series with the second filter ( $H_s$ ), or both.

11. Lithographic projection apparatus according to claim 10, wherein

$$H_f(z) = 1 + H_l(z) \frac{z^{-(p+q)}}{m}, \text{ and}$$

$$H_s(z) = \frac{H_l(z)}{1 + H_l(z) \frac{z^{-(p+q)}}{m}}.$$

12. A position control system for controlling a position of a moveable object, the position control system comprising a position controller (6) outputting a position controller force ( $F_p$ ); and a position feedback circuit (22) feeding back a determined actual position (20) of the object to an input of the position controller (6),

characterized in that the position control system further comprises an acceleration control system (34) comprising

- a first acceleration circuit branch comprising a subtractor (8) into which the position controller force ( $F_p$ ) is input; and a first filter ( $H_f$ ) having a first gain ( $K_f$ ) and into which the output of the subtractor

(8) is input, the output of the first filter (Hf) being exerted on the object; and

- a second acceleration circuit branch comprising a second filter (Hs) having a second gain (Ks) and into which an acceleration control signal is input, the output of the second circuit branch being input into said subtractor (8) to subtract the output of the second circuit branch from the position controller force (Fp)

5

13. A device manufacturing method comprising a step of  
10 controlling a position of at least one moveable object, in particular a substrate, a patterning means, or both; wherein the step of controlling a position comprises the steps of:

- exerting a control force (Fc) on said moveable object;
- determining an actual position (20) of said moveable
- 15 object;
- feeding back said position (20) to an input of a position controller (6),

characterized by

- subtracting a filtered acceleration control signal from  
20 a position controller force (Fp) output by the position controller (6) using a subtractor (8) comprised in a first acceleration circuit branch;
- filtering the output of the subtractor (8) using a first filter (Hf) having a first gain (Kf) comprised in the  
25 first acceleration circuit branch;
- determining an acceleration of said moveable object;
- filtering an acceleration control signal using a second filter (Hs) having a second gain (Ks) comprised in a second acceleration circuit branch; and
- 30 - supplying the output of the second acceleration circuit branch to the subtractor (8) comprised in the first

acceleration circuit branch.