

-1-

Lithographic Apparatus and Device Manufacturing Method.

The present invention relates to a lithographic projection apparatus comprising:

- a radiation system for supplying a projection beam of radiation;
- a support structure for supporting patterning means, the patterning means serving to
5 pattern the projection beam according to a desired pattern;
- a substrate table for holding a substrate;
- a projection system for projecting the patterned beam onto a target portion of the substrate;
- a base frame;
- 10 - a balance mass; and
- a positioning actuator connected between said substrate table or said support structure and said balance mass for generating a reaction force between said balance mass and said substrate table or said support structure thereby to position said substrate table or said support structure relative to said projection system.

15

The term “patterning means” as here 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 context. Generally,
20 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 it includes mask types such as binary, alternating phase-shift, and attenuated phase-shift, as well as
25 various hybrid mask types. Placement of such a mask in the radiation beam causes selective transmission (in the case of a transmissive mask) or reflection (in 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
30 incoming radiation beam, and that it can be moved relative to the beam if so desired.

-2-

- 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 (electromagnetic, electrostatic), 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 to 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.
- A programmable LCD array. An example of such a construction is given in United States Patent US 5,229,872, which is incorporated 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 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 case, the patterning means may generate a circuit pattern corresponding to an individual layer of the IC, and this pattern can be

-3-

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 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

5 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 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. In an alternative apparatus — commonly referred to as a step-and-scan apparatus — each target portion is irradiated by

10 progressively scanning the mask 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 information with

15 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 is at least partially covered by a layer of radiation-sensitive material (resist). Prior to this imaging step, the substrate may

20 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 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,

25 ion-implantation (doping), metallization, oxidation, chemo-mechanical polishing, etc., all intended to finish 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 individual devices

30 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 herein by reference.

-4-

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 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 (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 WO 98/40791, incorporated herein by reference.

In a lithographic projection apparatus, the information on a Mask that is positioned on a support structure, is projected on the Substrate table in a so-called scanning process, where the support structure and substrate table move synchronously at constant speed. The acceleration or deceleration forces can be high because the acceleration of the substrate table can typically be of the order of 5 to 100 m/s² and a substrate table might typically weigh about 10-200 [Kg]. If this substrate table is moved by an actuator that is attached to a Base Frame, the reaction force is transferred to this base frame. If this reaction force is directly transferred to the Base Frame, this results in large excitations of the Base Frame Eigen Frequencies (typically 10 to 50 [Hz]). This results in Base Frame vibrations that disturb the Vibration Isolation System of the Projection Lens. Part of the vibration can then be transmitted to the Projection Lens. Because the Substrate Table is positioned relative to the Projection Lens, this Projection Lens vibration will generate servo position errors, affecting the imaging process.

The effect of such a reaction force can be reduced by use of a freely mounted balance mass as described in US patent 6,262,796. This is done by generating a reaction force using a positioning actuator between the substrate table and the balance mass such that the substrate table is moved in one direction whilst the balance mass is moved in the opposite direction by an amount equal to the distance moved by the substrate table times the mass ratio of the substrate table to the balance mass. In this way, no substantial reaction forces are transmitted to the base frame and the combined center of gravity of the balance mass and the substrate table relative to the base frame stays substantially constant.

-5-

If such freely mounted balance mass has a large stroke, the balance mass requires guidance in its movement and the transmission of cables and tubes carrying utilities to the balance mass, in particular if the balance mass is in a vacuum, can be difficult to arrange and results in a large machine.

5 In an attempt to minimize the size of lithographic projection apparatus the mass of the balance mass can be increased to reduce the stroke required of the mass balance at the cost of extra complexity in the near frictionless support of the balance mass.

 The above problems are equally applicable to the support structure for supporting the patterning means which also needs to move relative to the projection system
10 and can be moved with the use of a balance mass.

 It is an object of the present invention to provide an alternative to the freely mounted balance mass that at least partly eliminates one of the above mentioned problems.

 This and other objects are achieved according to the invention in a
15 lithographic apparatus as specified in the opening paragraph, characterized in that said balance mass is coupled to said base frame via an elastic coupling so that said balance mass has a suspension eigenfrequency of between 0.3 and 10 Hz such that a portion of said reaction force is exerted on said base frame.

 In this way, only part of the reaction force is transmitted to the base frame
20 through the elastic coupling. An eigen frequency of between 0.3 and 10 Hz of the balance mass is preferred because then only low frequency vibrations are transmitted to the base frame as follows: reaction forces generated by movement of the substrate table or support structure at frequencies above about 10 to 15 Hz are hardly transmitted to the base frame as at these frequencies the balance mass is unaffected by the elastic coupling and behaves
25 almost as a free balance mass for these frequencies . Unwanted disturbances of the substrate table or support structure typically are disturbances with frequencies well above 10 Hz but the balance mass does not transfer significant disturbances in this frequency region. However, acceleration forces generated by long stroke operations of the substrate table or support structure, which typically have an energy with a frequency of below 10 Hz,
30 are transmitted to the base frame. Part of the reaction force on the balance mass is taken up by the spring stiffness of the elastic coupling and this requires a small stroke. It has been found that such low frequency forces transmitted to the base frame can be quite high in magnitude before they have a deleterious effect on the apparatus. In this way, in a typical lithographic projection apparatus according to the present invention the stroke of the

-6-

balance mass is typically less than about 20 mm. The elastic coupling may as an example comprise of leaf-springs, torsional springs or other mechanical springs, magnet assemblies with spring-like characteristics, etc. Furthermore, it is noted that, the elastic coupling has the tendency to move the balance mass to its neutral position. This yields for example, advantages during initialization of said positioning actuator.

In an embodiment according to the present invention, the balance mass is further supported via a bearing to the base frame. The bearing can, as an example, be an air bearing between the base frame and the balance mass. This provides a support allowing the balance mass to make the required stroke in the translational direction.

In an embodiment according to the present invention, the apparatus is constructed and arranged such that on movement during positioning of said substrate table or said support structure the position of the combined center of gravity of said substrate table or said support structure and said balance mass relative to said base frame also moves. Due to the elastic coupling of the balance mass to the base frame, the center of gravity will not maintain its position on movement during positioning of said substrate table or said support structure.

In an embodiment of the present invention, the apparatus further comprises a balance mass actuator for controlling the position of said balance mass. In this active embodiment, the balance mass actuator can be positioned in parallel with said elastic coupling, wherein the balance mass is also coupled to said base frame via said balance mass actuator. This balance mass actuator may be used to apply position correction forces to the balance mass at a low frequency. In this way, large but low frequency forces in the translational direction can be applied to the base frame at low frequency. The balance mass actuator may also enable a damping of the resonance frequency of the Balance Mass system (formed by the mass of the Balance Mass and the stiffness to Base Frame of the elastic coupling) and a further decrease in force transfer in the frequency range above 10Hz between the base frame and the balance mass.

In an embodiment of the present invention, a filtered feed forward program is applied to the balance mass actuator to smooth out the forces passed to the base frame. The balance mass actuator may, for example be a pneumatic, hydraulic, electromagnetic or piezo-electric actuator.

In another embodiment of the present invention, the apparatus comprises a spring-damper system positioned in parallel with said elastic coupling, wherein the balance mass is also coupled to said base frame via said spring-damper system. The spring-damper

-7-

system may combine different types of springs (mechanical, air, magnetic) with different types of dampers for example, a viscous damper, an eddy current damper, etc. In order to obtain the required transfer characteristic both series and parallel connections of springs and dampers may be applied. An advantage of the passive embodiment is that it provides a less expensive solution and is generally more robust than an active solution at the expense of some performance.

Preferably, the spring-damper system comprises at least one element having the characteristics of a spring connected in series with at least one element having the characteristic of a damper. In an embodiment where the elastic coupling substantially has the characteristics of a spring, this system is further on referred to as the KDK-system. The damper could be implemented as a viscous damper or any other type of damper.

Preferably, the damper is implemented as an Eddy current damper, since this gives advantages in the area of endurance, reliability, maintainability and contamination. This KDK-system enables a damping of the resonance frequency of the Balance Mass system (formed by the mass of the Balance Mass and the stiffness to Base Frame of the elastic coupling) and a further decrease in force transfer in the frequency range above 10Hz between the base frame and the balance mass. The spring damper system may also be realized by applying components that incorporate both characteristics of a spring and a damper such as rubber like materials or memory alloys.

In an embodiment of the present invention, the balance mass is damped with a damper with a damping coefficient, b , of between 0.3 and 0.9, preferably 0.65 to 0.75. In this way long stroke reaction forces of the substrate table applied to the base frame cannot amplify.

In an embodiment of the present invention, the damper is positioned in parallel with said elastic coupling, wherein the balance mass is also coupled to said base frame via said damper. The damping may be realized by a separate component or can be obtained by the elastic coupling itself with internal damper.

In an embodiment of the present invention, the balance mass is damped with a damping coefficient, b , which is varied as a function of frequency. As an example, an Eddy current damper may be applied. Also, in case a balance mass actuator is used for actively damping vibrations of said balance mass the damping coefficient can be varied as a function of frequency.

-8-

In an embodiment of the present invention, the apparatus further comprises a controller for periodically applying a position control loop. This may, as an example be applied to prevent drift of said balance mass due to repetitive motions of said substrate table or support structure or to compensate for friction of the balance mass or to correct
5 hysteresis effects of the elastic coupling.

In an embodiment of the present invention, between 50 and 100 % of the reaction force with a frequency below 3 to 10 Hz is exerted by said elastic coupling on said base frame.

In an embodiment of the present invention, the apparatus further comprises
10 a vacuum chamber containing the substrate table or support structure and the balance mass. The balance mass of the present invention is particularly suited to such applications because of its small stroke.

In an embodiment of the present invention, a bellows is applied between the balance mass and a wall of the vacuum chamber. This is possible because of the small
15 stroke of the balance mass and is advantageous because any cables and tubes to provide utilities to the balance mass, for example, such as air for air bearings or electrical cables for positional sensors, can be routed through the bellows and do not therefore need to be vacuum compliant.

In an embodiment of the present invention the bellows form at least part of
20 the elastic coupling. Depending on the stiffness, the bellows may partly or completely take over the function of the elastic coupling between the balance mass and the base frame.

In an embodiment of the present invention, the balance mass actuator or the spring-damper system is connected with said balance mass through said bellows. According to a further aspect of the invention there is provided a device manufacturing
25 method comprising the steps of:

- providing a substrate that is at least partially covered by a layer of radiation-sensitive material on a substrate table positioned on a base frame;
- providing a projection beam of radiation using a radiation system;
- using patterning means supported on a support structure to endow the projection
30 beam with a pattern in its cross-section;
- projecting the patterned beam of radiation onto a target portion of the layer of radiation-sensitive material;
- moving said substrate table or said support structure relative to said base frame by generating a reaction force between said substrate table or said support structure and a

balance mass,

characterized in transmitting part of said reaction force to said base frame through an elastic coupling which couples said balance mass to said base frame with a suspension eigenfrequency of between 0.3 and 10 Hz.

5 Although specific reference may be made in this text to 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, liquid-crystal display panels, thin-film magnetic
10 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
15 encompass all types of electromagnetic radiation, including ultraviolet radiation (e.g. with a wavelength of 365, 248, 193, 157 or 126 nm) and EUV (extreme ultra-violet 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
20 only, with reference to the accompanying schematic drawings in which:

 Figure 1 depicts the relevant parts of a lithographic projection apparatus;

 Figure 2 depicts a lithographic projection apparatus according to an embodiment of the invention;

 Figure 3 depicts a lithographic projection apparatus according to an
25 embodiment of the invention suitable for vacuum applications

 Figure 4 depicts a typical force pattern during the scanning process in both time and frequency domain.

 Figure 5 depicts the transfer of the reaction force to the base frame in the frequency domain for different embodiments of the present invention.

30 Figure 6 depicts the transfer function of the Balance Mass displacement to the base frame force in the frequency domain for different embodiments of the present invention.

-10-

Figures 7 depicts the KDK-system connecting the base frame an the balance mass according to an embodiment of the present invention

Figure 8 depicts an alternative arrangement for connection of the balance mass to the base frame according to an embodiment of the invention.

5 Figure 9 depicts an other alternative arrangement for connection of the balance mass to the base frame according to an embodiment of the invention.

Figure 10 schematically depicts a KDK-system comprising an Eddy current damper.

10 Figure 11 schematically depicts a Balance Mass that is coupled in 3 degrees of freedom in the horizontal plane.

In the Figures, corresponding reference symbols indicate corresponding parts.

15 Figure 1 schematically depicts the relevant parts of a lithographic projection apparatus. The apparatus comprises:

- a radiation system Ex, IL, for supplying a projection beam PB of radiation (e.g. I-line, UV, EUV radiation, Electron Beam etc.), which in this particular case also comprises a radiation source LA;
 - 20 · 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 substrate
 - 25 table positioning means PW for accurately positioning the substrate with respect to item PL;
 - a projection system ("lens") PL (e.g. a mirror system) 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.
- 30 As here depicted, the apparatus is of a reflective type (i.e. has a reflective mask). However, in general, it may also be of a transmission type, for example (with a transmissive mask). Alternatively, the apparatus may employ another kind of patterning means, such as a programmable mirror array of a type as referred to above.

-11-

The source LA (e.g. a laser-produced discharge plasma source) 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 Ex, for example. The illuminator IL may comprise adjusting means AM for setting the outer and/or inner radial extent (commonly referred to as σ -outer and σ -inner, respectively) of the intensity distribution in the beam. In addition, it will generally comprise various other components, such as an integrator IN and a condenser CO. In this way, the beam PB impinging on the mask MA has a desired uniformity and intensity distribution in its cross-section.

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 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 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 (and interferometric measuring means IF), the substrate table WT can be moved accurately, e.g. so as to position different target portions C in the path of the beam PB. Similarly, the first positioning means 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 (course positioning) and a short-stroke module (fine positioning), which are not explicitly depicted in Figure 1. It is noted that generally, the long stroke module enables long stroke movements of the substrate table substantially in a plane, while the long stroke module of the mask table enables long stroke movements substantially in one direction. 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 enabling short stroke movements in six degrees of freedom, or may be fixed.

The depicted apparatus can be used in two different modes:

-12-

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;
- 5 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
 10 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 invention will be described with reference to the substrate table WT. However, the invention is equally applicable to the mask table MT.

15 As can be seen from Figure 1 a typical Lithographic apparatus comprises a base frame BF on which the various components are supported.

As an example, the mounting of the various components to the base frame is illustrated schematically in Figure 2. This figure shows the base frame BF which is preferably stiffly connected to the ground 10. The projection system PL is isolated from
 20 vibrations of the base frame BF by being mounted on a metrology frame 50 which is compliantly connected to the base frame BF with a soft suspension system 55 of an active vibration isolation system (AVIS). The Wafer Table is driven by an actuator (20) and the reaction force is set on the Balance Mass (BM). An elastic coupling 150 is connected
 25 between the balance mass and the Base Frame. The stiffness of the elastic coupling 150 is chosen such that the balance mass is mounted on the Base Frame BF with a suspension eigenfrequency in the translational (horizontal) plane of between 0.3 and 10 Hz preferably 1 to 6 Hz. A suitable suspension eigenfrequency is about 3 Hz.

The suspension eigenfrequency f_0 can be calculated according to equation (1):

$$30 \quad f_0 = \frac{1}{2\pi} \sqrt{\frac{k_{spring}}{m_{BM}}}, \quad (1)$$

wherein k_{spring} is the stiffness of the spring of the elastic coupling 150 and m_{BM} is the mass of the balance mass BM. Arranging for the suspension eigenfrequency of

-13-

the balance mass to be in the range of 0.3 to 10 Hz ensures that a large but low frequency force dump into the base frame from the balance mass is allowed in both directions in the translational horizontal plane (forces of up to about 5000 N at a frequency of less than 3 Hz). In this example, in parallel with the elastic coupling 150, a damper 170 is placed and a
 5 Balance Mass actuator 100. The elastic coupling 150, the damper 170 and the Balance Mass actuator may optionally be enclosed by a bellows 120. In this way, the elastic coupling, the damper and the balance mass actuator are sealed off from the compartment wherein the substrate table WT and the Balance Mass are located. The use of bellows may impose less stringent conditions on the elastic coupling, the damper and the balance mass
 10 actuator with respect to contamination or outgassing properties, etc.,

The balance mass actuator 100 is used to correct the position of the balance mass which can have a tendency to drift from the correct position. This drift, which can be thought of as hysteresis, can be as a result of friction between the Base Frame BF and the balance mass BM, for example. The correction is applied as a closed loop control by having a controller
 15 which controls the balance mass actuator 100 and periodically (for example every millisecond) applies a force, if necessary, to center the balance mass BM substantially to prevent drift of the balance mass resulting from repetitive motions of the substrate table.

The actuator 100 may also be used to damp movement of the balance mass BM to avoid windup i.e. resonance of the balance mass BM. Alternatively, this function
 20 may be performed by the separate mechanical passive damper 170. Whatever form of damping is used, the relative damping coefficient, b , is preferably between 0.5 and 1.0 and more preferably between 0.65 to 0.75. If the balance mass actuator 100 is used, it may be used as an active damper, the damping coefficient, b , being varied as a function of frequency. For example, a damping coefficient of $b = 0.7$ may be used up to a threshold
 25 frequency (of, for example, in the region of 0.3 to 20 Hz) after which the damping coefficient reduces such that at a frequency of infinity, the damping coefficient is zero. In this way, the force transfer from Balance Mass to Base Frame at high frequencies is less than that for the case where the damping coefficient is constant. This damping also reduces the amplitude of the force transfer from Balance Mass to base frame for frequencies of
 30 movement of the substrate table WT close to the suspension eigenfrequency of the balance mass BM.

The balance mass actuator 100 may also be used to smooth the force profile transmitted at low frequencies to the base frame using a filtered feed forward program. This is done by passing the expected reaction force of the balance mass BM on the Base

-14-

Frame BF through a low pass filter and applying a force through the balance mass actuator 100 to the balance mass BM which smoothes out the sharp changes in reaction force. High frequency disturbances are not passed to the Base Frame in any case.

5 Figure 3 shows an alternative arrangement of the various components supported by the base frame BF for use in vacuum applications. In this example, the substrate table WT is positioned on a substrate table support frame SF (which is stiffly connected to the base frame BF) via connecting means 12. The Wafer Table is driven by an actuator (20) and the reaction force is set on the Balance Mass (BM). An elastic coupling 150 parallel with a
10 Balance Mass actuator 100 and a damper 170 are connected between the Balance Mass and the substrate table support frame. In this embodiment, the projection system PL, balance mass BM and substrate table WT are enclosed by a vacuum chamber VC that is stiffly connected to the base frame BM.

Both the substrate table WT and balance mass BM are mounted such that translational
15 movement in the horizontal plane parallel to the surface of the substrate table support frame SF is substantially frictionless. This can be achieved, for example, by suspending the substrate table WT from the balance mass and providing the balance mass with air bearings or providing both the substrate table and the balance mass with air bearings such that their weight can be supported by the substrate table support frame SF. The balance
20 mass may also be suspended on elastic mechanical or pneumatic springs.

On actuation of the positioning actuator 20 to generate a reaction force, the substrate table WT and balance mass BM will translate in opposite directions.

The balance mass BM is elastically coupled to the substrate table support frame SF and thereby to the base frame BF with an elastic spring coupling 150. The
25 stiffness of the elastic coupling 150 is chosen such that the balance mass is mounted on the wafer stage support frame SF with a suspension eigenfrequency in the translational (horizontal) plane of between 0.3 and 10 Hz preferably 1 to 6 Hz. A suitable suspension eigenfrequency is about 3 Hz.

Figure 4 shows the acceleration and deceleration forces that typically occur during
30 the scanning process. Acceleration and deceleration forces are shown both in the time domain and in the frequency domain. In this example, In this example the maximal acceleration force is about 1500 [N]. Also the Power Spectrum or the energy per frequency band is shown. Typically the acceleration profile Power Spectrum shows large forces at frequencies below 20 [Hz]. Above this frequency the remaining energy is very small.

-15-

Applying a suspension eigenfrequency in the range of 0.3 to 10 Hz for the Balance Mass, short stroke translational movements of the substrate table WT, which occur at frequency of about 10-15 Hz and above, are hardly transferred to the base frame as the Balance Mass acts here in a conventional free mass manner. However, for long stroke

5 translational movements of the substrate table WT, which occur at a low frequency of below about 15 Hz, at least a part of the reaction force is transferred to the substrate table support frame SF and thereby to the base frame BF. Thus, the displacement required of the balance mass for low frequency movements is reduced as a portion of the reaction force (between 50 and 100%) is exerted on the substrate table support frame SF via the elastic

10 coupling 150. It has been found that such large but low frequency force dumps in the horizontal translational direction can be applied to the base frame BF (typically about 1000-5000 N at frequencies of less than 3 Hz) without deleterious effects to the performance of the apparatus.

15 Figure 5 shows the Bode plots of transfer of Balance Mass forces to the Base Frame for a number of embodiments of the present invention. This figure shows the Balance Mass force to Base Frame force ratio (in dB) vs. the frequency [Hz]. As a reference, the characteristic of a freely mounted Balance Mass (i.e a Newton Balance Mass) is shown as graph G0. A perfect Balance Mass that operates according to Newtons 'action = reaction'

20 Law, will absorb all energy and thus cannot transmit forces to the Base Frame. A less perfect Newton Balance Mass will partly transmit a very small amount of force with low frequencies. A Newton Balance Mass has the disadvantage that the motion or excursion is equal to the mass ratio of Balance Mass and Substrate Table.

If an elastic coupling is connected between the Balance Mass and the Base Frame, the

25 Balance Mass excursion can be much reduced. The effect however is that low frequency forces are directly transmitted (to the base Frame) and that at the resonance frequency the Base Frame force can be much higher than the Balance Mass force, as is shown in graph G1. Above the resonance frequency, the undamped Balance Mass again reduces the force dump into the Base Frame and forms a mechanical filter with a roll-off of -40 [dB/dec].

30 The amplification at the resonance frequency is reduced by applying a passive damper in parallel with the elastic coupling between the Balance Mass and the Base Frame as shown in graph G3. However the mechanical filter of this Damped Balance Mass then only has a roll-off of -20 [dB/dec].

-16-

When the damping element is formed by a damper in series with a spring, this combined system of elastic coupling and spring-damper system, also referred to as the KDK-system, again has a roll-off of -40 [dB/dec], although the filtering starts at a higher frequency. As is shown in graph G3, the performance of this KDK-system Balance Mass is superior to the

5 Damped Balance Mass shown in G2.

In an other embodiment, a control loop formed by an actuator between the Balance Mass and Base Frame and a position sensor that measures the position of the Balance Mass relative to the Base Frame is applied. The controller can be adjusted in such a way that both the damping of the resonance frequency is obtained and the steep -40 [dB] roll off is

10 maintained, see graph G4.

Figure 6 depicts the Bode plots of the transfer of the Balance Mass motion to the Reaction Force is plotted. At low frequencies, the Balance Mass motion as function of the input force is proportional to the inverse of the stiffness of the elastic coupling. So a stiffness of

15 $1e5$ [N/m] between Balance Mass and Base Frame will result in $1e-5$ [m] displacement per 1 [N] input force (so the transfer is $1e-5$ [m/N] or -100 dB). For 1500 [N] the displacement is about 15 mm. If the stiffness is increased, the motion is reduced by the same factor, but also the frequency band for the output forces is increased (see figure 6 and eq. 1). So a soft elastic coupling comes with soft forces (strong Balance Mass filtering) but also a large

20 excursion. A stiff elastic coupling has hard forces (poor filtering) but a small excursion. Somehow a suitable compromise between Balance Mass excursion and Force Filtering performance can be found. The use of an elastic coupling that has a non-linear characteristic may be applied to accommodate this compromise. Both linear and non-linear springs-type elements may be applied to realize this. These elements can be arranged

25 between balance mass and base frame in such manner that the stiffness progressively increases when the balance mass is displaced from its neutral position.

Near the resonance frequency, the displacement will be amplified if no damping is present (the amplification shown in figure 6 is approx. $100 \times$!). In order to avoid this, a damping element should be combined with the elastic coupling. Graph G1 in figure 6 shows the

30 characteristics of the undamped system, G2 shows the characteristics of the damped system, G3 shows the characteristics of the KDK-system and G4 shows the characteristics of the elastic coupling combined with the Balance Mass actuator. In the damped systems (G2,G3,G4), the amplification occurring in the undamped system at the resonance frequency is attenuated. For high frequencies all systems have a -40 dB/dec roll off, so

-17-

forces with very high frequency can only generate small Balance Mass displacements.

Figure 7 schematically depicts an embodiment of the present invention, wherein the KDK-system is applied between the Balance Mass and the Base Frame. The KDK-system is a passive system that comprises an elastic coupling 150 in parallel with a spring-damper system 180 that comprises an element having the characteristics of a spring in series with an element having the characteristics of a damper. This KDK-system can be applied in combination with a bellows 120 enclosing the KDK-system enabling the use of materials or components that are not vacuum-compliant for the KDK-system. The bellows may also take over, partly or completely, the function of the elastic coupling 150. The KDK-system as shown in figure can also be applied inside an embodiment as shown in figure 3, as an alternative to elastic coupling combined with a balance mass actuator.

In a vacuum application, the balance mass BM is connected to the wall of the vacuum chamber VC by metal bellows 120 which may be manufactured from welding a curved plate or buckling a wide pipe with thin walls. The bellows allow the elastic coupling 150 and the actuator 100 or the KDK-system to be placed outside of the vacuum chamber VC such that their design requirements are less stringent as they do not need to be vacuum compliant (for example meet out-gassing criteria). Furthermore, utilities can be provided to the balance mass BM through the bellows 120 via pipes or cables. The use of bellows 120 is possible because of the small stroke which the balance mass BM undergoes during positioning of the substrate table WT. The bellows may form at least part of the elastic coupling of the balance mass BM to the base frame.

Figure 8 shows an alternative layout for the connection of the balance mass BM to the base frame which, in this embodiment, is part of the vacuum chamber wall VC. The elastic coupling 150 and balance mass actuator 100 are housed in the substrate table vacuum chamber within a secondary vacuum chamber 210 which may conveniently be at higher pressure than the substrate table vacuum chamber VC. A connection member 200 connects the elastic coupling 150 and balance mass actuator 100 to the substrate table vacuum chamber wall VC. A seal or bellow is required between the secondary vacuum chamber 200 and the connection chamber. In alternative illustrated in Figure 9, the connection member 200 connects the balance mass BM to the elastic coupling 150 and the balance mass actuator 100 which are directly connected to the base frame BF. The substrate table vacuum chamber VC is separate from the base frame in this embodiment

-18-

such that the balance mass actuator BM does not need to be vacuum compliant as it is positioned outside of the vacuum. A seal is required between the substrate table vacuum chamber VC and the connection member 200.

Figure 10 schematically depicts a KDK-system connected between the
 5 Balance Mass BM and the Base Frame BF. The Balance Mass is supported by the Bearing system 215. The KDK-system comprises an elastic coupling 150 and a spring-damper system comprising springs 240 and an Eddy current damper comprised of Magnet plates 220 and a conducting plat 230 positioned between both Magnet Plates.

10 The balance mass BM can have 1 to 6 degrees of freedom , but preferable 3 degrees of freedom (in the horizontal plane) or 6 degrees of freedom (both in the horizontal and vertical plane). The coupling as described by the present invention between balance mass and support frame is applicable in all degrees of freedom in which the substrate table or support structure have movements. The elastic coupling between balance mass and
 15 support frame may have different properties for the different degrees of freedom. The elastic coupling may further be combined with a balance mass actuator and/or a spring-damper system having different properties for the different degrees of freedom. As an example, Figure 11 shows a top view of a possible arrangement wherein the elastic couplings 150 are springs between a balance mass BM and a base frame BF. It should be
 20 clear that the depicted elastic coupling may be combined with the KDK-system or combined with a damper and a Balance Mass actuator. It should also be noted that in this arrangement the Balance Mass is coupled in 3 degrees of freedom (X,Y and Rz) although only springs in X and Y direction are applied. This method for defining the elastic coupling in different degrees of freedom can also be applied for more than 3 degrees of freedom.

25

Whilst specific embodiments of the invention have been described above, it will be appreciated that the invention may be practiced otherwise than as described. The description is not intended to limit the invention.

CLAIMS:

1. A lithographic projection apparatus comprising:
 - a radiation system for providing a projection beam of radiation;
 - a support structure for supporting patterning means, the patterning means serving to pattern the projection beam according to a desired pattern;
 - a substrate table for holding a substrate;
 - a projection system for projecting the patterned beam onto a target portion of the substrate;
 - a base frame;
 - a balance mass;
 - a positioning actuator connected between said substrate table or said support structure and said balance mass for generating a reaction force between said balance mass and said substrate table or said support structure thereby to position said substrate table or said support structure relative to said projection system, and
 - a balance mass actuator for controlling the position of said balance mass relative to said base frame,characterized in that said balance mass is coupled to said base frame via an elastic coupling so that said balance mass has a suspension of Eigen frequency of between 0.3 and 10 Hz such that a portion of said reaction force is exerted on said base frame wherein said balance mass actuator is positioned in parallel with said elastic coupling, wherein the balance mass is also coupled to said base frame via the balance mass actuator.
2. An apparatus according to claim 1, characterized in that the balance mass is supported by the base frame via a bearing.
3. An apparatus according to claims 1 or 2, constructed and arranged such that on movement during positioning of said substrate table or said support structure the position of the combined center of gravity of said substrate table or said support structure and said balance mass relative to said base frame also moves.
4. An apparatus according to one of claims 1 to 3, further comprising a balance mass actuator for controlling the position of said balance mass,
5. An apparatus according to claim 4, wherein said balance mass actuator is positioned in parallel with said elastic coupling, wherein the balance mass is also coupled to said base frame via the balance mass actuator.

-20-

6. An apparatus according to one of claims 1 to 3, further comprising a spring-damper system positioned in parallel with said elastic coupling, wherein the balance mass is also coupled to said base frame via the spring damper system.

5 7. An apparatus according to claim 6 wherein the spring-damper system comprises at least one element having the characteristics of a spring connected in series with at least one element having the characteristic of a damper.

8. An apparatus according to claim 7 wherein said spring-damper system
10 comprises an Eddy current damper.

9. An apparatus according to claim 4 or 5, wherein, in use, vibration of said balance mass due to said elastic coupling is actively damped by said balance mass actuator.

15 10. An apparatus according to any one of claim 1 to 9, wherein, in use, vibration of said balance mass generated due to said elastic coupling is damped with a damper with a damping coefficient, b , of between 0.5 and 1.0, preferably 0.65 to 0.75.

11. An apparatus according to claim 10 wherein said damper is positioned in
20 parallel with said elastic coupling, wherein the balance mass is also coupled to said base frame via said damper.

12. An apparatus according to any one of claims 9 to 11, wherein said balance mass is damped with a damping coefficient, b , which is varied as a function of frequency.

25

13. An apparatus according to any one of claims 4, 5 or 9, further comprising a controller for controlling said balance mass actuator and for periodically applying a position control loop substantially to prevent drift of said balance mass due to repetitive motions of said substrate table or said support structure.

30

14. An apparatus according to any one of the preceding claims, wherein between 50 and 100% of said reaction force with a frequency below 3 to 10Hz is exerted by said elastic coupling on said base frame.

-21-

15. An apparatus according to any one of the preceding claims, wherein a bellows extends between said balance mass and said base frame.

16. An apparatus according to any one of the preceding claims, further comprising a vacuum chamber containing said substrate table or said support structure and said balance mass.

17. An apparatus according to claim 16, wherein said base frame forms part of the wall portions of said vacuum chamber and wherein a bellows extends between said balance mass and said wall portions.

18. An apparatus according to claim 15 or 17, wherein said bellows forms at least part of said elastic coupling.

19. An apparatus according to claim 17 or 18, wherein said balance mass actuator or said spring-damper system is connected with said balance mass through said bellows.

20. An apparatus according to any of the preceding claims, characterized in that the stiffness of the elastic coupling is a function of the relative position of the balance mass with respect to the base frame.

21. An apparatus according to claim 4, 5, 9 or 13, characterized in that the lithographic apparatus further comprises a feed forward controller for controlling the balance mass actuator.

22. An apparatus according to any of the preceding claims, characterized in that the elastic coupling is applied in at least 3 degrees of freedom to the balance mass.

23. A device manufacturing method comprising the steps of:

- providing a substrate that is at least partially covered by a layer of radiation-sensitive material on a substrate table positioned on a base frame;
- providing a projection beam of radiation using a radiation system;
- using patterning means supported on a support structure to endow the projection beam with a pattern in its cross-section;
- projecting the patterned beam of radiation onto a target portion of the layer of radiation-sensitive material;

-22-

- moving said substrate table or said support structure relative to said base frame by generating a reaction force between said substrate table or said support structure and a balance mass,

characterized in transmitting part of said reaction force to said base frame through an

5 elastic coupling which couples said balance mass to said base frame with a suspension eigenfrequency of between 0.3 and 10 Hz.