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Exposure apparatus, exposure method, and article manufacturing method

Abstract

An exposure apparatus that performs an exposure operation of exposing a substrate via a projection optical system is provided. The apparatus includes a temperature regulator configured to regulate a temperature distribution on an optical element of the projection optical system, and a controller configured to perform, in an exposure operation period in which the exposure operation is executed, a first process of controlling the temperature regulator so as to reduce a change of aberration of the projection optical system caused by execution of the exposure operation. In accordance with detection of a predetermined event before the exposure operation period, the controller performs, before performing the first process, a second process for reducing the aberration of the projection optical system using a method different from the first process.

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Background/Summary

BACKGROUND OF THE INVENTION
Field of the Invention
(1) The present invention relates to an exposure apparatus, an exposure method, and an article

manufacturing method.
Description of the Related Art
(2) In the manufacturing of an article such as a semiconductor device, an exposure apparatus that illuminates an original (a reticle or a mask) by an illumination optical system, projects a pattern of the original onto a substrate via a projection optical system, and exposes the substrate is used. Since the imaging characteristics of the projection optical system fluctuate due to irradiation of exposure light, the imaging characteristics are corrected properly.
(3) For example, Japanese Patent No. 5266641 describes that the imaging characteristics are corrected by applying a temperature distribution to an optical element using a heater element. However, when the imaging characteristics are corrected using the heater element as described in Japanese Patent No. 5266641, if the time constant concerning the temperature of the projection optical system is smaller than the time constant concerning heating by the heater element, the correction accuracy decreases. On the other hand, Japanese Patent No. 5334945 describes a method of starting correction before the imaging characteristics of the projection optical system fluctuate.
(4) Japanese Patent No. 5334945 describes that a correction mechanism is controlled precedingly based on the change of the gradient of the time-temperature characteristic of the imaging characteristics. However, depending on the detection timing of the change of the gradient, the correction residual cannot be reduced sufficiently.
SUMMARY OF THE INVENTION
(5) In consideration of the above-described problems, the present invention provides a technique advantageous in correcting the aberration of a projection optical system with high accuracy.
(6) The present invention in its one aspect provides an exposure apparatus that performs an exposure operation of exposing a substrate via a projection optical system, the apparatus including a temperature regulator configured to regulate a temperature distribution on an optical element of the projection optical system, and a controller configured to perform, in an exposure operation period in which the exposure operation is executed, a first process of controlling the temperature regulator so as to reduce a change of aberration of the projection optical system caused by execution of the exposure operation, wherein, in accordance with detection of a predetermined event before the exposure operation period, the controller performs, before performing the first process, a second process for reducing the aberration of the projection optical system using a method different from the first process.
(7) Further features of the present invention will become apparent from the following description of exemplary embodiments (with reference to the attached drawings).

Description

BRIEF DESCRIPTION OF THE DRAWINGS
(1) FIG. **1** is a view schematically showing the arrangement of an exposure apparatus;
(2) FIGS. **2**A and **2**B are views showing an arrangement example of an optical element and a temperature regulator;
(3) FIGS. **3**A and **3**B are views each showing the temperature distribution on a lens heated by the temperature regulator;
(4) FIG. **4** is a view exemplarily showing the distribution of a light beam that passes through a lens of a projection optical system of a scanning exposure apparatus;
(5) FIG. **5** is a graph exemplarily showing the temporal characteristic of the change of the astigmatism;
(6) FIG. **6** is a flowchart illustrating an astigmatism correction process;
(7) FIGS. **7**A and **7**B are graphs for explaining the effect of the astigmatism correction process;
(8) FIGS. **8**A and **8**B are graphs for explaining the effect of the astigmatism correction process in a

case in which lot processing operations of two lots are performed successively;
(9) FIG. **9** is a graph for explaining the effect of the astigmatism correction process in a case in which lot processing operations of two lots are performed successively;
(10) FIG. **10** is a block diagram showing a configuration example of a control system related to substrate conveyance;
(11) FIG. **11** is a flowchart illustrating an aberration correction process in a case in which lot processing is interrupted; and
(12) FIG. **12** is a flowchart illustrating an aberration correction process in a case in which a delay has occurred in conveyance of a substrate during lot processing.

DESCRIPTION OF THE EMBODIMENTS

(13) Hereinafter, embodiments will be described in detail with reference to the attached drawings. Note, the following embodiments are not intended to limit the scope of the claimed invention. Multiple features are described in the embodiments, but limitation is not made to an invention that requires all such features, and multiple such features may be combined as appropriate.
(14) Furthermore, in the attached drawings, the same reference numerals are given to the same or similar configurations, and redundant description thereof is omitted.

First Embodiment

(15) FIG. **1** schematically shows the arrangement of an exposure apparatus **10** according to the first embodiment. The exposure apparatus **10** schematically performs an exposure operation of exposing a substrate **110** via a projection optical system **107**. In this specification and the drawings, directions are indicated based on an XYZ coordinate system in which a plane parallel to a surface on which the substrate **110** is arranged is set as an X-Y plane, as shown in FIG. **1**. The exposure apparatus **10** includes a light source **102**, an illumination optical system **104**, the projection optical system **107**, a controller **100**, and a temperature controller **111**. In an exposure operation, the illumination optical system **104** illuminates an original **106** with light (exposure light) from the light source **102**, and the pattern of the original **106** is projected onto the substrate **110** by the projection optical system **107** to expose the substrate **110**. The exposure apparatus **10** may be formed as an exposure apparatus that exposes the substrate **110** in a state in which the original **106** and the substrate **110** are stopped still or as an exposure apparatus that exposes the substrate **110** while scanning the original **106** and the substrate **110**. In general, the substrate **110** includes a plurality of shot regions, and an exposure operation is performed on each shot region.
(16) The light source **102** can include, for example, an excimer laser, but may include another light-emitting device, or may be an electron gun. The excimer laser can generate, for example, light having a wavelength of 248 nm or 193 nm, but light of another wavelength can also be generated. The projection optical system **107** can include an optical element **109** and a temperature regulator **108** that controls the temperature distribution on the optical element **109**. The temperature regulator **108** can reduce the change of the optical characteristics of the projection optical system **107** by applying thermal energy to the optical element **109** to change the refractive index distribution and/or the surface shape of the optical element **109**. The thermal energy applied to the optical element **109** by the temperature regulator **108** can include positive energy and negative energy. Application of positive energy to the optical element **109** represents heating of the optical element **109**, and application of negative energy to the optical element **109** represents cooling of the optical element **109**.
(17) The temperature regulator **108** may be arranged to be tightly adhered to the optical element **109**, and the thermal energy transmission between the temperature regulator **108** and the optical element **109** will be efficient in such a case. Alternatively, the temperature regulator **108** may be arranged spaced apart from the optical element **109**. This arrangement is advantageous in the point that a mechanical force will not be applied to the optical element **109** by the temperature regulator **108**, and in the point that the temperature regulator **108** will not damage the optical element **109** by scratching or the like.

(18) It is preferable to arrange the temperature regulator **108** outside the effective diameter (optical path) of the optical element **109** so the temperature regulator **108** will not block the light irradiation to the substrate **110**. For example, the temperature regulator **108** can be arranged on the outer edge portion of a lens serving as the optical element **109**, the front surface of the lens, or the back surface of the lens. Alternatively, the temperature regulator **108** may be arranged inside the effective diameter in a range that will not influence the optical performance of the projection optical system **107**. As an example of such an arrangement, for example, a thin heating wire may be arranged in the effective diameter of the optical element or a heat transmitting element which has a high light transmittance may be arranged in the effective diameter of the optical element.
(19) When arranging the temperature regulator **108** on the outer periphery of the optical element **109**, the optical element **109** is preferably arranged at or near a pupil plane of the projection optical system **107**, but the temperature regulator **108** may be arranged spaced away from the pupil plane of the projection optical system **107**.
(20) In a period in which the exposure operation is executed and a period in which the exposure operation is not executed, the temperature regulator **108** can change the thermal energy to be applied to the optical element **109** in synchronization with the optical characteristics of the projection optical system **107** which change moment by moment. In this embodiment, the temperature controller **111** controls the temperature regulator **108**. The temperature controller **111** can control the amount of thermal energy applied to the optical element **109** and the continuation time of the application, and the temperature distribution on the optical element **109** can be controlled as a result. Here, information required for control of the temperature regulator **108** can be generated based on the result of measuring the optical characteristics of the projection optical system **107** on the image plane (the plane on which the substrate **110** is arranged) of the projection optical system **107**. Alternatively, information required for control of the temperature regulator **108** may be decided in advance through measurement or the like. Information required for control by the temperature controller **111** is obtained by measuring, in advance, the aberration generation amount of the optical element **109** upon being applied with heat under the exposure condition to be executed. Based on the information obtained by the measurement, the controller **100** decides the thermal energy to be applied to the optical element **109** during exposure, and gives an instruction including the information to the temperature controller **111**. The temperature controller **111** applies the thermal energy to the temperature regulator **108** using a control value corresponding to the given instruction. Control of the thermal energy to be applied to the optical element **109** by the temperature regulator **108** can be implemented by, for example, control of the current value to be applied to the heating wire if the temperature regulator **108** includes the heating wire. Alternatively, control of the thermal energy to be applied to the optical element **109** by the temperature regulator **108** may be implemented by, for example, control of the physical distance or thermal distance between the optical element **109** and the temperature regulator **108**.
(21) The controller **100** can control the light source **102**, the illumination optical system **104**, the projection optical system **107**, and the temperature controller **111**. The controller **100** can be formed from, for example, a Programmable Logic Device (PLD) such as a Field Programmable Gate Array (FPGA), an Application Specific Integrated Circuit (ASIC), a general-purpose or dedicated computer installed with a program, or a combination of all or some of these components. Note that in this embodiment, the controller **100** and the temperature controller **111** are formed as separate components, but the controller **100** may be formed so as to include the function of the temperature controller **111**.
(22) FIGS. **2**A and **2**B show an arrangement example of the optical element **109** and the temperature regulator **108**. FIG. **2**A is a plan view when viewed from the Z direction, and FIG. **2**B is a sectional view taken along a line A-A′ in FIG. **2**A. The optical element **109** can include a lens **201**. The temperature regulator **108** can include a first temperature regulator **203** formed from heater elements **203***a* and **203***b*, and a second temperature regulator **204** formed from heater

elements **204***a* and **204***b*.
(23) A circle **202** drawn with a broken line represents the light beam effective diameter of the lens **201**. Outside the light beam effective diameter, the heater element **203***a* and the heater element **203***b* are arranged at positions facing each other along the Y direction with the center of the lens **201** interposed therebetween, and the heater element **204***a* and the heater element **204***b* are arranged at positions facing each other along the X direction with the center of the lens **201** interposed therebetween. Each of the heater elements **203***a*, **203***b*, **204***a*, and **204***b* can have an arc shape corresponding to a length of one quarter of the circumference of the lens **201**. Each of the heater elements **203***a*, **203***b*, **204***a*, and **204***b* can be formed by, for example, a flexible cable including a heating wire, and heat is generated by applying a current to the heating wire, so that a temperature distribution can be generated in the lens **201**.
(24) For example, the heater elements **203***a*, **203***b*, **204***a*, and **204***b* can be arranged spaced apart from the planar portion of the lens **201** by 10 to 100 μm. The heat generated by each of the heater elements **203***a*, **203***b*, **204***a*, and **204***b* can be transferred to the lens **201** via a medium **205** between each of the heater elements **203***a*, **203***b*, **204***a*, and **204***b* and the lens **201**, respectively. The medium **205** can be, for example, a gas such as air or nitrogen. The heater elements **203***a*, **203***b*, **204***a*, and **204***b* need not directly face the lens **201** via the medium **205**. Each of the heater elements **203***a*, **203***b*, **204***a*, and **204***b* may have, for example, a structure in which a metal having high thermal conductivity sandwiches the heating wire.
(25) In the example shown in FIG. **2**B, the heater elements **203***a*, **203***b*, **204***a*, and **204***b* are arranged on the planar portion (on the side of the illumination optical system **104**) of the lens **201**. However, the heater elements **203***a*, **203***b*, **204***a*, and **204***b* may be arranged below (on the side of the substrate **110**) the lens **201** or on the outer edge portion of the lens **201**. The lens **201** can include a heated surface **206** which is heated by the heater elements **203***a*, **203***b*, **204***a*, and **204***b*. The heated surface **206** may be flat or curved. The heated surface **206** can be, for example, a roughened surface (a surface in the manner of frosted glass).
(26) FIG. **3**A exemplarily shows the temperature distribution on the lens **201** heated by the second temperature regulator **204**. At this time, astigmatism is generated on the surface of the substrate **110** in the positive direction. FIG. **3**B exemplarily shows the temperature distribution on the lens **201** heated by the first temperature regulator **203**. The temperature distribution shown in FIG. **3**B is a temperature distribution that has the opposite phase of the temperature distribution shown in FIG. **3**A. The temperature distribution shown in FIG. **3**B generates astigmatism on the surface of the substrate **110** in the negative direction. In this manner, positive astigmatism and negative astigmatism can be generated by heating the lens **201** by the first temperature regulator **203** and the second temperature regulator **204**. Compared to an arrangement in which the positive astigmatism and the negative astigmatism are generated by a combination of heating and cooling by using an element such as a Peltier element, this kind of arrangement is advantageous in that the arrangement of the temperature regulator **108** can be simplified.
(27) Here, consider a case in which the exposure apparatus **10** shown in FIG. **1** is a scanning exposure apparatus that scans the original **106** and the substrate **110** with respect to a long slit-shaped light beam (exposure light) in the X direction. In this case, the intensity distribution of the light beam that passes through the projection optical system **107** at the time of the exposure operation can be as that shown by a hatched portion **401** of FIG. **4**. In this case, the temperature distribution on the lens **201** (optical element **109**) generated by the absorption of the light beam will differ in the X direction and the Y direction. This can cause a large amount of astigmatism to be generated in the projection optical system **107**.
(28) Hence, a temperature distribution can be applied to the lens **201** by the temperature regulator **108** so as to reduce the astigmatism. The astigmatism generated by the temperature regulator **108** and the astigmatism generated when the lens **201** absorbs a light beam have opposite signs. Therefore, the astigmatism generated by the absorption of the light beam by the lens **201** can be

reduced (corrected) by the astigmatism generated by the temperature regulator **108**. Note that in the following description, “astigmatism” represents the astigmatism of the projection optical system **107** unless otherwise specified.
(29) The change (temporal change characteristic) of the astigmatism generated by the temperature regulator **108** may be different from the change (temporal change characteristic) of the astigmatism generated by the absorption of the light beam by the lens **201**. In this case, the current to be supplied to the heating wire of each of the heater elements **203***a*, **203***b*, **204***a*, and **204***b* is controlled to control the change of the astigmatism. With this, the astigmatism generated by the absorption of the light beam by the lens **201** can be canceled with higher accuracy.
(30) FIG. **5** exemplarily shows the temporal characteristic of the change of the astigmatism. In FIG. **5**, “exposure time” refers to an exposure operation period in which the exposure operation is executed, and “non-exposure time” refers to a non-exposure operation period preceding the exposure operation period, in which the exposure operation is not executed. The “exposure operation period” refers to the period from the start of the exposure operation on the first substrate to the end of the exposure operation on the last substrate in one lot. The “exposure operation period” also includes the period between shots in which no exposure is actually executed, and the substrate replacement period. The “non-exposure operation period” can include the period from the startup of the apparatus or the time at which the apparatus is in an idle state to the start of the exposure operation on the first substrate in the lot.
(31) In FIG. **5**, a curve **501** expresses the time-series change of the astigmatism generated by the absorption of heat of the exposure light by the lens **201** in the exposure operation period after the non-exposure operation period. An ideal method of reducing or canceling the astigmatism generated by the absorption of heat of the exposure light by the lens **201** is generating, by heating the lens **201** by the temperature regulator **108**, the astigmatism that changes in a curve corresponding to the curve **501** with the opposite sign. However, as expressed by a curve **502**, if the temperature regulator **108** continuously heats the lens **201** at a predetermined temperature, the astigmatism generated by this heating operation tends to change by a slower time constant than that of the curve **501**. Hence, the astigmatism expressed by the curve **501** cannot be completely corrected (canceled), and the correction residual as expressed by a curve **503** can be generated.
(32) In order to compensate for the inability of the correction by heating the lens **201** by the temperature regulator **108** to follow the change of the aberration during the exposure time, it is conceivable to additionally execute an aberration correction process at the time at which the aberration exceeds an allowable value. However, if the execution frequency of the additional correction process increases, productivity decreases. On the other hand, it is also conceivable to predict, using information of the lot in process and information of the succeeding lot, the amount of aberration generated in each of the two lots, and performing correction based on the prediction result. However, it is difficult to perform such the prediction with high accuracy due to the problems described below.
(33) In the following description, a series of exposure operations on respective substrates in a lot of substrates (a unit of a plurality of substrates to be processed under the same condition) is referred to as “lot processing”. In the exposure apparatus **10** or an external apparatus (such as a server), when a process instruction including the detailed information of the process to be executed for the lot is generated, and the process instruction is submitted to the exposure apparatus **10**, the lot processing is started. This process instruction is referred to as an “exposure job” hereinafter. The exposure job is a lot processing start instruction, and includes information concerning the conditions (for example, exposure amount, angle of view, scanning speed, transmittance of original, and the like) of the exposure operation on each substrate in the lot. Upon receiving the exposure job, the controller **100** performs an aberration correction process, which will be described below in detail, in accordance with the conditions of the exposure operation included in the exposure job, and then starts the exposure operation in the lot.

(34) Since the start timing of the exposure operation in the lot processing is planned and decided by the user, the accurate time difference between the submission timing of the exposure job of the lot processing and the start timing of the exposure operation in the lot processing corresponding to this is unknown. Therefore, the start timing of the exposure operation can be decided by at least one of statistical calculation from the past operational performance of the apparatus, prediction from the lot information and the apparatus status at the reception timing of the exposure job, and the like. The start timing of the exposure operation obtained based on the time decided as described above is referred to as an “assumed start timing” hereinafter.
(35) If the submission timing of the exposure job of the succeeding lot processing is immediately before the completion of the currently executing lot processing, the lens **201** cannot be sufficiently heated by the start of the succeeding lot processing, so that the correction residual can increase. Also, if the next exposure job is submitted while the exposure apparatus **10** is in the idle state, the correction cannot follow the change of the aberration immediately after the start of the lot processing, so that the correction residual can increase. For example, in FIG. **5**, a timing **504** indicates the reception timing of the exposure job by the controller **100**. A period **505** indicates the period from the reception timing **504** of the exposure job to the start of the exposure operation on the first substrate in the lot. In the example shown in FIG. **5**, the period **505** is of about 100 sec. Even if the correction by heating the lens **201** by the temperature regulator **108** based on the prediction of the amount of aberration generated in the lot is executed within this period, it is difficult for the correction to follow the change of the astigmatism generated by the absorption of the light beam by the lens **201** during the exposure time.
(36) In this embodiment, aberration correction that can cope with the problems as described above is performed. FIG. **6** shows a flowchart illustrating an astigmatism correction process in this embodiment. This process is started in accordance with the reception of an exposure job by the controller **100**. In step S**601**, the controller **100** acquires the apparatus status and the lot information. The apparatus status is status information including information as to whether an exposure operation in lot processing is currently executed, information as to whether lot processing has been interrupted, information as to whether there is a substrate conveyance delay, and the like. The lot information is information included in the received exposure job, and can be information concerning the conditions (for example, exposure amount, angle of view, scanning speed, transmittance of original, and the like) of the exposure operation on each substrate in the lot.
(37) In step S**602**, the controller **100** predicts the aberration generation amount based on the apparatus status and the lot information acquired in step S**601**, and calculates the heating amount to be applied to the lens **201** by the temperature regulator **108** required to correct the predicted aberration. In calculation of the heating amount, in order to prevent a failure of the temperature regulator **108**, a restriction may be provided so as not to exceed the upper limit of the settable heating amount.
(38) In step S**603**, the controller **100** determines, if the heating amount calculated in step S**602** is applied to the lens **201** by the temperature regulator **108**, whether the correction by the temperature regulator **108** can follow the change of the astigmatism generated by the heat absorption by the lens **201** during the exposure time. In an example, if the time difference between the assumed start timing of the exposure operation and the reception timing of the exposure job is larger than a predetermined threshold value, it is determined that the correction can follow the change of the astigmatism. The predetermined threshold value can be decided based on the result of correction by the heating by the temperature regulator **108**. Alternatively, the predetermined threshold value may be decided based on the result of modeling and simulation of the astigmatism generated by the heating by the temperature regulator **108**. The aberration generation amount for the submitted lot processing may be predicted, and the predetermined threshold value may be dramatically changed base on the predicted aberration generation amount. In another example, if the difference between the pre-measured value of the astigmatism generated by the heat absorption by the lens **201** and the

aberration generation amount predicted in step S**602** is smaller than a predetermined threshold value, it is determined that the correction can follow the change of the astigmatism.

(39) If it is determined in step S**603** that the correction can follow the change of the astigmatism, the process advances to step S**605**. In step S**605**, the controller **100** controls the temperature regulator **108** via the temperature controller **111**, thereby immediately applying the heating amount calculated in step S**602** to the lens **201**. With this, the desired correction residual can be achieved.

(40) On the other hand, if it is determined in step S**603** that the correction cannot follow the change of the astigmatism, even if the heating amount calculated in step S**602** is applied to the temperature regulator **108**, the desired correction residual cannot be achieved. Accordingly, in this case, the process advances to step S**604**. In step S**604**, forced aberration correction is executed. The forced aberration correction includes at least one of processes listed below: (a) a process of applying a temperature distribution to the lens **201** by light irradiation (that is, by 0th-order light) without using the original, thereby generating the aberration having the opposite sign to the aberration amount generated by the lens **201** due to the exposure light; (b) a process of heating by the temperature regulator **108**, thereby generating the aberration having the opposite sign to the aberration amount generated by the lens **201** due to the exposure light; (c) stopping the lot processing until the state is achieved in which the change of the astigmatism generated by heating the lens **201** by the temperature regulator **108** can follow the change of the astigmatism generated by the heat absorption by the lens **201** during the exposure time; and (d) a process of cooling the lens **201** until the state is achieved in which the change of the astigmatism generated by heating the lens **201** by the temperature regulator **108** can follow the change of the astigmatism generated by the heat absorption by the lens **201** during the exposure time.

(41) With reference to FIGS. **7**A and **7**B, examples of the effects of the correction process illustrated in FIG. **6** will be described. Each of FIGS. **7**A and **7**B shows an improvement example of the correction residual in a case in which the reception timing of the exposure job is changed with respect to the temporal characteristic of the change of the astigmatism shown in FIG. **5**.

(42) In the example shown in FIG. **7**A, a reception timing **704** of the exposure job is earlier than the reception timing **504** of the exposure job in FIG. **5**, and a period **705** from the timing **704** to the assumed start timing of the exposure operation is of about 400 sec. Here, assume that the predetermined threshold value for the time difference between the assumed start timing of the exposure operation and the reception timing of the exposure job, which is used to determine whether the correction by heating the lens **201** by the temperature regulator **108** can follow the change of the aberration during the exposure time, is set to 300 sec. In this case, the period **705** is longer than the threshold value. Then, in step S**603**, it is determined that the correction by applying the heating amount calculated in step S**602** to the lens **201** by the temperature regulator **108** can follow the temporal change of the astigmatism generated by the heat absorption of the lens **201** during the exposure time. Accordingly, in this case, in step S**605**, the controller **100** starts the correction process by heating the lens **201** by the temperature regulator **108** immediately after the timing **704**. With this, the astigmatism generated by heating the lens **201** by the temperature regulator **108**, which is expressed by a curve **702**, corrects the change of the astigmatism generated by the heat absorption by the lens **201** during the exposure time, which is expressed by a curve **701**. The correction residual at this time, which is expressed by a curve **703** in FIG. **7**A, is reduced by an average of 1.5 nm with respect to the correction residual expressed by the curve **503** in FIG. **5**.

(43) Also in the example shown in FIG. **7**B, assume that the above-described predetermined threshold value is set to 300 sec as in the above description concerning FIG. **7**A. In FIG. **7**B, a reception timing **709** of the exposure job is earlier than the reception timing **504** of the exposure job in FIG. **5** by about 100 sec. In other words, a period **710** from the reception timing **709** to the assumed start timing of the exposure operation is longer than the period **505** shown in FIG. **5** by about 100 sec. However, the period **710** is shorter than the threshold value. Accordingly, it is determined in step S**603** that the correction by applying the heating amount calculated in step S**602**

to the lens **201** by the temperature regulator **108** cannot follow the temporal change of the astigmatism generated by the absorption of the light beam by the lens **201** during the exposure time. Therefore, in this case, the controller **100** executes the forced aberration correction in step S**604**.

(44) Here, assume that as the forced aberration correction, a process is executed in which a temperature distribution is applied to the lens **201** by 0th-order light to generate the aberration having the opposite sign (negative direction) to the aberration amount generated by the lens **201** due to the exposure light. With this process, the astigmatism of −2.8 nm can be generated as expressed by a curve **711**. Thereafter, in step S**605**, at an assumed start timing **712** of the exposure operation, the controller **100** controls the temperature regulator **108** via the temperature controller **111** to start the correction by applying the heating amount calculated in step S**602** to the lens **201**. As a result, the astigmatism generated by heating the lens **201** by the temperature regulator **108**, which is expressed by a curve **707**, follows the astigmatism generated by the heat absorption by the lens **201** during the exposure time, which is expressed by a curve **706**, thereby correcting (canceling) the astigmatism. The correction residual at this time, which is expressed by a curve **708** in FIG. **7**B, is reduced by an average of 1.2 nm with respect to the correction residual expressed by the curve **503** in FIG. **5**.

(45) FIGS. **8**A and **8**B show an example of improvement of the correction residual by the correction process in a case in which an exposure job of next lot processing is submitted during the lot processing.

(46) In FIG. **8**A, the same characteristic as in FIG. **7**A is shown in the period from 0 sec to 2,200 sec. Here, it is planned to execute the first lot processing including a series of exposure operations on a plurality of substrates in the first lot, and the second lot processing including a series of exposure operations on a plurality of substrates in the second lot after the first lot processing. However, a reception timing **804** of the exposure job of the second lot by the controller **100** is close to the end of the lot processing of the first lot, and about 100 sec before the assumed start timing of the exposure operation of the second lot. That is, a period **805** from the timing **804** to the assumed start timing of the exposure operation of the second lot is of about 100 sec. Assuming that the predetermined threshold value for the time difference between the assumed start timing of the exposure operation and the reception timing of the exposure job is set to about 300 sec as in the above description concerning FIG. **7**A, the period **805** is shorter than the threshold value. Accordingly, it is determined in step S**603** that the astigmatism generated by applying the heating amount calculated in step S**602** to the lens **201** by the temperature regulator **108** cannot follow the change of the astigmatism generated by the absorption of the light beam by the lens **201** during the exposure time. Therefore, in this case, the controller **100** executes the forced aberration correction in step S**604**.

(47) FIG. **8**B shows the result obtained by executing the forced aberration correction in step S**604** since the exposure job of the second lot was received at the timing **804** as in FIG. **8**A. Here, as the forced aberration correction, a method is executed in which the lot processing is stopped until the state is achieved in which the change of the astigmatism generated by heating the lens **201** by the temperature regulator **108** can follow the change of the astigmatism generated by the heat absorption by the lens **201** during the exposure time. With this method, the lot processing is stopped in a period **809** of about 400 sec. With this, the aberration generated by the exposure for the first lot can be reduced by 8 nm. In addition, during this stop period, heating of the lens **201** by the temperature regulator **108** in step S**605** can be executed. In this manner, a waiting period is provided so as to reduce the aberration of the projection optical system **107** before the second lot processing is started. With this, the astigmatism generated by heating the lens **201** by the temperature regulator **108**, which is expressed by a curve **807**, follows the change of the astigmatism generated from an exposure start timing **810** of the second lot, which is expressed by a curve **806**, thereby correcting (canceling) the astigmatism. The correction residual at this time

during the exposure time of the second lot, which is expressed by a curve **808** in FIG. **8**B, can be reduced by an average of 2.7 nm with respect to the correction residual expressed by a curve **803** in FIG. **8**A.

(48) FIG. **9** shows another example of the result of the correction process in the case in which the exposure job of next lot processing is received during the lot processing. The same characteristic of the first lot as in FIGS. **8**A and **8**B is shown in FIG. **9** and, as in the example shown in FIGS. **8**A and **8**B, it is planned to start the lot processing of the second lot immediately after the lot processing of the first lot is complete. In FIG. **9**, a reception timing **904** of the exposure job of the second lot is about 400 sec before the assumed start timing of the exposure operation of the second lot. That is, a period **905** from the reception timing **904** to the assumed start timing of the exposure operation of the second lot is of about 400 sec. Assuming that the predetermined threshold value for the time difference between the assumed start timing of the exposure operation and the reception timing of the exposure job is set to 300 sec as in the above descriptions concerning FIG. **7**A and FIG. **8**A, the period **905** is longer than the threshold value. Accordingly, it is determined in step S**603** that the astigmatism generated by applying the heating amount calculated in step S**602** to the lens **201** by the temperature regulator **108** can follow the change of the astigmatism generated by the absorption of the light beam by the lens **201** during the exposure time. Therefore, in this case, the forced aberration correction in step S**604** is not executed, and heating of the lens **201** by the temperature regulator **108** is executed in step S**605** as usual. With this, the astigmatism generated by heating the lens **201** by the temperature regulator **108**, which is expressed by a curve **902**, follows the change of the astigmatism generated by the heat absorption by the lens **201** during the exposure time of the second lot, which is expressed by a curve **901**, thereby correcting (cancelling) the astigmatism. The correction residual at this time during the exposure time of the second lot, which is expressed by a curve **903** in FIG. **9**, can be reduced by an average of 3.0 nm with respect to the correction residual expressed by the curve **803** in FIG. **8**A.

Second Embodiment

(49) As has been described above, since the start timing of the exposure operation in the lot processing is planned and decided by the user, the accurate time difference between the submission timing of the exposure job of the lot processing and the start timing of the exposure operation in the lot processing corresponding to this is unknown. Therefore, the start timing of the exposure operation can be decided by at least one of statistical calculation from the past operational performance of the apparatus, prediction from the lot information and the apparatus status at the reception timing of the exposure job, and the like.

(50) However, with these methods, if a sudden abnormality occurs, it is difficult to decide the accurate time. To solve this problem, in this embodiment, in order to decide the more accurate time, information of the conveyance time of the substrate to an exposure apparatus **10** is acquired from a preprocessing device that performs a preprocess on the substrate and, based on the acquired information, decides the assumed start timing. The preprocessing device can be a coating/developing device (coater/developer) that performs a process of coating a substrate with a resist (photosensitive agent) as a preprocess for the exposure process and also performs a developing process as a postprocess for the exposure process.

(51) FIG. **10** shows a configuration example of a control system related to substrate conveyance. As shown in FIG. **10**, the exposure apparatus **10** can include a controller **100** and a conveyance control device **1001**. Note that the arrangement of the exposure apparatus **10** except for the controller **100** and the conveyance control device **1001** follows FIG. **1**, and illustration thereof is omitted in FIG. **10**. The conveyance control device **1001** regularly inquires a preprocessing device **1002** about the scheduled loading timing of the first substrate in the succeeding lot. In response to the inquiry, the preprocessing device **1002** calculates the conveyance timing of the substrate to the exposure apparatus **10** based on the substrate processing status and the substrate supply status in the preprocessing device **1002**, and notifies the conveyance control device **1001** of the information.

The conveyance control device **1001** transmits the notified information to the controller **100**. Based on the received information of the conveyance timing of the substrate to the exposure apparatus **10**, the controller **100** decides the assumed start timing.

(52) As has been described above, by using the information notified from the preprocessing device **1002**, it is possible to decide the assumed start timing with high accuracy.

Third Embodiment

(53) FIG. **11** is a flowchart illustrating an aberration correction process in a case in which an error occurs during lot processing and the lot processing is interrupted.

(54) In step S**1101**, as a predetermined event, a controller **100** detects interruption of the currently executing lot processing (a series of exposure operations). In step S**1102**, the controller **100** stops the aberration correction process by a temperature regulator **108** performed during the lot processing. In step S**1103**, a recovery process for the error that has occurred is performed. The recovery process may be manually performed by the engineer, or may be automatically performed by an exposure apparatus **10**.

(55) In step S**1104**, the controller **100** determines whether the recovery process in step S**1103** is complete. If the recovery process is not complete, the process returns to step S**1103**. If the recovery process is complete, the process advances to step S**1105**.

(56) In step S**1105**, the controller **100** decides the time until the restart of the lot processing. The time until the restart of the lot processing may be decided using a preset time, or may be decided based on the contents of the error that have caused the interruption of the lot processing, the contents of the performed recovery process, or the like.

(57) In step S**1106**, the controller **100** predicts the aberration generation amount based on the time decided in step S**1105** and the lot information, and calculates the heating amount to be applied to a lens **201** by the temperature regulator **108** required to correct the predicted aberration.

(58) Contents of subsequent steps S**1107**, S**1108**, and S**1109** are similar to those of steps S**603**, S**604**, and S**605** of FIG. **6**, respectively.

Fourth Embodiment

(59) FIG. **12** is a flowchart illustrating an aberration correction process in a case in which a delay has occurred in conveyance of a substrate during lot processing.

(60) In step S**1201**, a controller **100** acquires the scheduled substrate loading time notified from, for example, a preprocessing device **1002**. In step S**1202**, the controller **100** determines, based on the acquired scheduled loading time, whether a substrate conveyance delay has occurred. For example, when there is no substrate in an exposure apparatus **10**, if the scheduled substrate loading time notified from the preprocessing device **1002** is later than a scheduled time by a predetermined time or more, a conveyance delay is detected as a predetermined event. If no conveyance delay has occurred, the process returns to step S**1201**. If a conveyance delay has been detected, the process advances to step S**1203**.

(61) In step S**1203**, the controller **100** predicts the aberration generation amount based on the scheduled substrate loading time acquired in step S**1201** and the lot information, and calculates the heating amount to be applied to a lens **201** by a temperature regulator **108** required to correct the predicted aberration.

(62) Contents of subsequent steps S**1204**, S**1205**, and S**1206** are similar to those of steps S**603**, S**604**, and S**605** of FIG. **6**, respectively.

(63) <Embodiment of Article Manufacturing Method>

(64) An article manufacturing method according to an embodiment of the present invention suitably manufactures an article, for example, a microdevice such as a semiconductor device or an element having a microstructure. The article manufacturing method of this embodiment includes a step of forming a latent pattern by using the above-described exposure apparatus on a photosensitive agent applied on a substrate (an exposure step of exposing the substrate), and a development step of developing the substrate exposed in the exposure step. Further, the article

manufacturing method includes a processing step of processing the substrate developed in the development step. The processing step includes other well-known steps (oxidation, film formation, deposition, doping, planarization, etching, resist removal, dicing, bonding, packaging, and the like). In the article manufacturing method, an article is obtained from the substrate processed in the processing step. The article manufacturing method of this embodiment is more advantageous than the conventional methods in at least one of the performance, quality, productivity, and production cost of the article.
(65) While the present invention has been described with reference to exemplary embodiments, it is to be understood that the invention is not limited to the disclosed exemplary embodiments. The scope of the following claims is to be accorded the broadest interpretation so as to encompass all such modifications and equivalent structures and functions.
(66) This application claims the benefit of Japanese Patent Application No. 2022-067118, filed Apr. 14, 2022, which is hereby incorporated by reference herein in its entirety.

Claims

1. An exposure apparatus that performs a first exposure operation of exposing a plurality of substrates of a first lot via a projection optical system and a second exposure operation of exposing a plurality of substrates of a second lot, to be exposed after the first lot, via the projection optical system, the apparatus comprising: a temperature regulator configured to regulate a temperature distribution on an optical element of the projection optical system; and a controller configured to perform, in an exposure operation period in which the second exposure operation is executed, a first process of controlling the temperature regulator so as to reduce a change of aberration of the projection optical system caused by execution of the second exposure operation, wherein, in a case in which the controller receives an instruction for an exposure job of the second lot during the first exposure operation, and determines that a time difference between an assumed start timing of the second exposure operation and a reception timing of the instruction for the exposure job of the second lot is smaller than a predetermined threshold value, the controller performs, in a non-exposure operation period between the first exposure operation and the second exposure operation and before performing the first process, a second process for reducing the aberration of the projection optical system using a method different from the first process.
2. The apparatus according to claim 1, wherein the controller is configured to, upon detecting an interruption of the first exposure operation or the second exposure operation, determine a time until the interrupted exposure operation is restarted, and predict an amount of aberration of the projection optical system based on the determined time.
3. The apparatus according to claim 1, wherein the temperature regulator is arranged outside an effective diameter of the optical element, and is configured to partially apply heat to the optical element by the first process.
4. The apparatus according to claim 3, wherein the second process includes one of controlling a temperature distribution applied to the optical element by light irradiation, providing a waiting period before entering the exposure operation period, and cooling the optical element.
5. The apparatus according to claim 1, wherein upon detecting a conveyance delay of the substrate, the controller obtains a scheduled loading time of the substrate and predicts an amount of aberration of the projection optical system based on the obtained scheduled loading time.
6. The apparatus according to claim 1, wherein the controller acquires information of a conveyance time of the substrate to the exposure apparatus from a preprocessing device that performs a preprocess on the substrate and, based on the acquired information, decides the assumed start timing.
7. The apparatus according to claim 1, wherein each of the first process and the second process is a process of reducing astigmatism as the aberration.

8. An exposure method of performing a first exposure operation of exposing a plurality of substrates of a first lot via a projection optical system and a second exposure operation of exposing a plurality of substrates of a second lot, to be exposed after the first lot, via the projection optical system, the method comprising: performing, in an exposure operation period in which the second exposure operation is executed, a first process of controlling a temperature distribution on an optical element of the projection optical system by a temperature regulator so as to reduce a change of aberration of the projection optical system caused by execution of the second exposure operation, and performing, in a case in which an instruction for an exposure job of the second lot is received during the first exposure operation, and it is determined that a time difference between an assumed start timing of the second exposure operation and a reception timing of the instruction for the exposure job of the second lot is smaller than a predetermined threshold value, a second process for reducing the aberration of the projection optical system using a method different from the first process, the second process being performed in a non-exposure operation period between the first exposure operation and the second exposure operation and before performing the first process.

9. An article manufacturing method comprising: exposing a substrate by an exposure method defined in claim 8; developing the substrate exposed in the exposing; and processing the substrate developed in the developing, wherein an article is obtained from the substrate processed in the processing.