(12) INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(51) International Patent Classification[7]: G03F 7/20

(21) International Application Number:
PCT/EP2005/008392

(22) International Filing Date: 3 August 2005 (03.08.2005)

(25) Filing Language: English

(26) Publication Language: English

(30) Priority Data:
60/599,055 6 August 2004 (06.08.2004) US

(71) Applicant (for all designated States except US): CARL ZEISS SMT AG [DE/DE]; Carl-Zeiss-Strasse 22, 73447 Oberkochen (DE).

(72) Inventor; and
(75) Inventor/Applicant (for US only): GEH, Bernd [DE/US]; 12814 N 89th Place, Scottsdale, Arizona 85260 (US).

(74) Agent: RUFF, WILHELM, BEIER, DAUSTER & PARTNER; Kronenstrasse 30, 70174 Stuttgart (DE).

(81) Designated States (unless otherwise indicated, for every kind of national protection available): AE, AG, AL, AM, AT, AU, AZ, BA, BB, BG, BR, BW, BY, BZ, CA, CH, CN, CO, CR, CU, CZ, DE, DK, DM, DZ, EC, EE, EG, ES, FI, GB, GD, GE, GH, GM, HR, HU, ID, IL, IN, IS, JP, KE, KG, KM, KP, KR, KZ, LC, LK, LR, LS, LT, LU, LV, MA, MD, MG, MK, MN, MW, MX, MZ, NA, NG, NI, NO, NZ, OM, PG, PH, PL, PT, RO, RU, SC, SD, SE, SG, SK, SL, SM, SY, TJ, TM, TN, TR, TT, TZ, UA, UG, US, UZ, VC, VN, YU, ZA, ZM, ZW.

(84) Designated States (unless otherwise indicated, for every kind of regional protection available): ARIPO (BW, GH, GM, KE, LS, MW, MZ, NA, SD, SL, SZ, TZ, UG, ZM, ZW), Eurasian (AM, AZ, BY, KG, KZ, MD, RU, TJ, TM), European (AT, BE, BG, CH, CY, CZ, DE, DK, EE, ES, FI, FR, GB, GR, HU, IE, IS, IT, LT, LU, LV, MC, NL, PL, PT, RO, SE, SI, SK, TR), OAPI (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, ML, MR, NE, SN, TD, TG).

Published:
— without international search report and to be republished upon receipt of that report

[Continued on next page]

(54) Title: PROJECTION OBJECTIVE FOR MICROLITHOGRAPHY

(57) Abstract: A projection objective for imaging a pattern arranged in an object surface of the projection objective into an image surface of the projection objective with a demagnified imaging scale has a plurality of optical elements which are arranged along an optical axis of the projection objective and are configured in such a way that a defined image field curvature of the projection objective is set in such a way that an object surface that is curved convexly with respect to the projection objective can be imaged into a planar image surface. What can be achieved given a suitable setting of the object surface curvature is that a gravitation-dictated bending of a mask does not have a disturbing effect on the imaging quality.

WO 2006/013100 A2

<u>Description</u>

Projection objective for microlithography

BACKGROUND OF THE INVENTION

5 <u>Field of the invention</u>

[0001]   The   invention   relates   to   a   projection
objective for imaging a pattern of a mask arranged in
an object surface of the projection objective into an
10 image field arranged in the image surface of the
projection objective with a demagnifying imaging scale,
and to a microlithography projection exposure apparatus
having such a projection objective.

15 <u>Description of the related prior art</u>

[0002]   Photolithographic projection objectives with
a demagnifying imaging scale (reduction objectives)
have   been   used   for   several   decades   for   the
20 photolithographic   fabrication   of   semiconductor
components and other finely patterned devices. They
serve for projecting the pattern of a mask, e.g. of a
photomask or of a reticle, onto an article coated with
a light-sensitive layer with very high resolution on a
25 demagnifying scale.

[0003]   Conventional projection systems are designed
to image a planar mask onto a planar image field.

- 2 -

Accordingly, measures for correcting the image field
curvature (Petzval correction) are provided in the
projection objectives. The article "New lenses for
microlithography" by E. Glatzel in: SPIE Vol. 237
5   (1980), pp. 310 - 320, describes known measures for
leveling the image field.

[0004]   The patent US 5,052,763 describes a
catadioptric projection objective with intermediate
10   image, wherein the image of the object field
(intermediate image) generated by a first, catadioptric
subsystem is imaged into the image plane with the aid
of a second, refractive subsystem. In order to be able
to image a planar object into a planar image surface,
15   the Petzval sum of the system is obtained by
compensation of the image field curvature generated by
the first subsystem by means of the second subsystem, a
curved intermediate image surface being generated.

20   [0005]   The patent US 4,812,028 describes a
microlithography projection objective having aplanatic
refracting surfaces, non-aplanatic refracting surfaces
and reflective surfaces. The Petzval sums of the
aplanatic refracting surfaces and of the remaining
25   surfaces are corrected independently of one another.

[0006]   For projection lithography onto curved
substrates, the US patent US 6,461,908 B1 proposes
using a curved mask whose form is identical to the form
30   of the curved substrate. The curved mask is produced in
a contact method. Curvature-conforming imaging of the
curved mask onto the curved substrate requires
projection objectives with a substantial correction of
the image field curvature.
35
[0007]   The US patent US 5,527,139 discloses a purely
reflective reduction objective for extreme ultraviolet
radiation (EUV), wherein the object surface and/or the

- 3 -

image surface are curved concavely with respect to the projection objective.

[0008]   The   patent   application   US 2003/0133087 A1 describes   a   method   by   which   imaging   errors   that   may result   on   account   of   the   gravitational-force-dictated curvature   of   a   reticle   are   intended   to   be   prevented. This   involves   taking   account   of   the   fact   that   a gravitational-force-dictated   mask   bending   can   lead   to   a distortion   of   the   pattern   situated   on   the   mask   (pattern stretching),   so   that   errors   similar   to   a   distortion error   result   in   the   image   of   the   pattern.   In   order   to correct   these   errors,   an   optical   correction   element designed   for   a   distortion   correction   is   introduced between   the   object   plane   and   the   projection   objective.

SUMMARY OF THE INVENTION

[0009]   It   is   an   object   of   the   invention   to   provide   a projection   objective   by   means   of   which   adverse influences   of   the   force   of   gravity   on   the   imaging quality can be avoided.

[0010]   This   object   is   achieved,   in   accordance   with   a formulation   of   the   invention,   by   means   of   a   projection objective   for   imaging   a   pattern   arranged   in   an   object surface   of   the   projection   objective   into   an   image surface   of   the   projection   objective   with   a   demagnified imaging   scale,   the   projection   objective   having   a plurality   of   optical   elements   which   are   arranged   along an   optical   axis   of   the   projection   objective   and   are configured   in   such   a   way   that   a   defined   finite   image field   curvature   of   the   projection   objective   is   set   in such   a   way   that   an   object   surface   that   is   curved convexly   with   respect   to   the   projection   objective   can be imaged into a planar image surface.

[0011]   The   projection   objective   is   thus

- 4 -

distinguished by the fact that a predetermined, finite value is provided for the image field curvature in order intentionally to enable a non-curvature-conforming or curvature-altering imaging between the

5   curved object surface and the optically conjugate, planar image surface or image plane with respect thereto.

[0012]   As is known, the image field curvature

10 dependent only on the radii of the refracting surfaces and the refractive indices of the optical components, with astigmatism eliminated and correction of the remaining aberrations, leads to the punctiform imaging of an object plane that is orthogonal with respect to

15 the optical axis onto a curved image surface, the peak curvature of which is referred to as the Petzval curvature. The Petzval curvature is proportional to the Petzval sum $1/R_P$, the reciprocal of which is the Petzval radius R_P.

20

[0013]   Conventional systems are set to a value of the Petzval sum as close as possible to 0, so that the Petzval radius R_P should be infinite. The Petzval correction, i.e. the correction of the image field

25 curvature, is typically performed such that the magnitude of the Petzval sum is small in relation to the depth of focus DOF, e.g. in accordance with $|R_P| < 0.1$ DOF. As is known, the depth of focus is proportional to λ/NA^2, where λ is the operating

30 wavelength and NA is the image-side numerical aperture of the projection objective. Projection objectives according to the invention deviate substantially from this design goal with regard to the correction of the image field curvature, so that a bias of the image

35 field curvature is created. In advantageous embodiments of projection objectives according to the invention, the following holds true: $|R_P| \geq 0.1$ DOF.

- 5 -

[0014]   In this case, the projection objective has an object surface that is curved convexly with respect to the projection objective. Thus surface curvature is opposite to the "natural" surface curvature of a lens system with a positive refractive power overall and no or only weak Petzval correction and also a planar image surface. Accordingly, the measures provided for correction of the image field curvature are intensified in comparison with a similar system with a planar object surface and planar image plane in the sense of an overcorrection of the image shell.

[0015]   A preferred embodiment with an object surface that is curved convexly with respect to the projection objective is optimized toward taking account of a gravitation-dictated bending of the mask by means of corresponding measures for influencing the image field curvature. The projection objective is provided for utilization with an optical axis that is oriented vertically in the region of the object surface, and the object surface is curved in such a way that an effective object surface curvature in at least one direction perpendicular to the optical axis essentially corresponds to a gravitation-dictated mask bending of the mask. As a result, the pattern of a mask that has bent on account of gravity influences between bearing surfaces can on average be imaged sharply into a planar image surface, it being possible to avoid typical errors attributed to image field curvature. In the case of such projection objectives, the gravitation-dictated portion in the error budget is obviated, as a result of which stabler processes are made possible.

[0016]   This aspect of the invention is based on the consideration that, for a given construction of a mask holder (reticle stage) and a predetermined mask construction (with regard to size, thickness, material, etc.), a "fingerprint" of the gravitation-dictated

bending of the mask exists which is characteristic of these conditions and which is always present in the same way as a systematic contribution and is translated into a bending of the image surface with the square of the imaging scale in the case of a Petzval-corrected system. The resultant contributions to the image field curvature in the region of the substrate to be exposed may perfectly well be of the order of magnitude of 10 to 50 nm, in particular of 20-30 nm, in present-day systems. These contributions may be tolerable as long as they are small relative to the depth of field or depth of focus (DOF) of the projection objective. However, the latter decreases drastically as the image-side numerical aperture NA increases and the wavelength λ decreases, to be precise linearly with λ and with the square of the numerical aperture. Therefore, the image errors resulting from a gravitation-dictated mask bending may be disturbing, particularly in systems having high numerical apertures, for example NA > 0.8 or > 0.85. These problems are avoided in the embodiments mentioned

[0017]   The gravitation-dictated bending of the mask is cylindrical to a first approximation in many mask holding systems and cannot be completely biased in a rotationally symmetrical objective design. The situation is different, however, in the case of projection objectives for wafer scanners, in which the mask is moved relative to the projection objective in a scanning direction perpendicular to the optical axis during the exposure operation (with synchronous movement of the substrate to be exposed). On account of the scanning operation, a rotationally symmetrically curved object surface of the projection objective is translated into an effectively cylindrically curved object surface of the scanner system since only a certain excerpt from the object surface is utilized for the imaging. A projection objective designed for a

- 7 -

curved object surface which is curved in such a way
that a scanner-integrated object surface curvature
corresponds to the surface curvature produced by
gravitation-dictated reticle bending can sharply image
5   a bent mask into a planar image surface over the entire
image field.

[0018]   In the case of projection objectives in
scanner systems, this means that a cylindrical mask
10   bending can be taken into account well through suitable
correction of the image field curvature near the
projection objective. In the case of projection
objectives for stepper systems, in particular, in which
the mask and the article to be exposed are stationary
15   during the exposure, it may be advantageous if at least
one optical element of the projection objective bears
at least one nonrotationally symmetrical surface, for
example a toric surface.

20   [0019]   The projection objective may be corrected
with regard to all field-dependent image errors (e.g.
distortion), with the exception of the image field
curvature. Preferably, it is also corrected well with
regard to field-independent image errors, such as
25   spherical aberration, so that essentially only the
image field curvature remains as uncorrected image
error.

[0020]   In the design of the projection objective, it
30   must be taken into consideration that the image shell
error that leads to an image field curvature or to a
non-curvature-conforming imaging produces a variation
of the image position over the image field. In contrast
thereto, distortion is a variation of the image size.
35   Therefore, the two errors can be fundamentally
distinguished from one another. The image shell,
represented e.g. by the Petzval curvature, is
influenced by the sum of all surface refractive powers,

- 8 -

to be precise first and foremost by means of the radii
of the refracting surfaces and secondly by the
refractive indices. At least the lowest-order image
field curvature cannot be corrected by aspheres. The
5   distortion, by contrast, can be influenced by
deflecting the main imaging beam in the tangential
direction. The distortion can be corrected at locations
with large principal vay heights by means of suitable
radii and thicknesses of lenses, but also by means of
10   aspheres. In contrast to the correction of the image
shell, the distortion cannot be influenced in the
vicinity of the aperture diaphragm.

[0021]   In order to produce a projection objective
15   according to the invention, the following procedure is
preferably adopted. Firstly, the projection objective
is calculated in a conventional manner such that it is
suitable for imaging a planar object surface into a
planar image surface that is optically conjugate with
20   respect thereto, with a corresponding imaging scale. A
lens is then picked out in the case of which the
surface radius is altered at one of the lens surfaces
so as to result in the desired change in the Petzval
sum or the image field curvature. The system is
25   subsequently tuned, for example by adapting air
clearances between the individual lenses in order to
minimize alternations brought about by this
modification in the case of other aberrations. In the
case of new construction of projection objectives, such
30   a lens which leads to a desired overcorrection of the
image shell may be provided from the outset. If
existing systems are intended to be optimized in
accordance with the invention, then it is possible to
exchange a lens provided at a suitable location for a
35   lens with a changed surface radius and then to carry
out the corresponding tuning.

[0022]   Well-correctable projection objectives are

- 9 -

possible in the context of the invention. There are embodiments which are designed as "dry objectives". Dry objectives are distinguished by the fact that they are designed for a gas-filled gap to be present during operation between the exit side of the projection objective and the coupling-in surface of an article to be exposed, for example a wafer, the gap width of said gap typically being significantly greater than the operating wavelength. In the case of such systems, the numerical apertures that can be achieved are restricted to values of NA < 1, since, when approaching the value NA = 1, total reflection conditions occur at the exit surface and prevent illumination light from being coupled out from the exit surface. In preferred embodiments of dry systems, the image-side numerical aperture is NA > 0.8, NA ≥ 0.85 or NA ≥ 0.9 also being possible.

[0023]   Projection objectives designed as immersion objectives are also possible in the context of the invention. In the case of immersion lithography, as is known, the resolution that can be achieved in an exposure process is improved by introducing an immersion medium having a high refractive index, for example an immersion liquid having a refractive index n_I ≥ 1.3 at the operating wavelength, into the space between the last optical element of the projection objective and the substrate. Projection objectives or imagings having an image-side numerical aperture NA > 1.0 are possible as a result, preferably NA ≥ 1.1 or NA ≥ 1.2 or NA ≥ 1.3 being possible.

[0024]   The optical construction also permits a use for contactless near field projection lithography. In this case, it is possible for sufficient light energy to be coupled into the substrate to be exposed via a gas-filled gap if a sufficiently small image-side operating distance is complied with on average over

- 10 -

time. Said operating distance should be less than four times the operating wavelength used, in particular less than the operating wavelength. It is particularly favorable for the operating distance to be less than half of the operating wavelength, for example less than a third, a quarter or a fifth of the operating wavelength. Given these short operating distances, an imaging in the optical near field may be effected in the case of which evanescent fields that exist in direct proximity to the last optical surface of the imaging system are utilized for imaging.

[0025] The invention can be used in purely refractive projection objectives as well as in catadioptric projection objectives.

[0026] The above and further features emerge not only from the claims but also from the description and the drawings, in which case the individual features may be realized in each case on their own or as a plurality in the form of subcombinations in an embodiment of the invention and in other fields and may represent advantageous and intrinsically protectable embodiments.

BRIEF DESCRIPTION OF THE DRAWINGS

[0027]
Figure 1   schematically   shows,   in   an   oblique perspective illustration, an excerpt from a microlithography   projection   exposure apparatus with an embodiment of a projection objective according to the invention;

[0028]
figure 2   shows   a   schematic   illustration   of   the rotationally   symmetrical,   curved   object surface   of   the   projection   objective   in figure 1 with a scanner slot;

[0029]

- 11 -

figure 3   shows a schematic illustration of the form of
            the effective object surface of the
            projection objective which is produced as a
            result of scanning movement;

[0030]

figure 4   shows a measured bending of a standard
            reticle in a schematic illustration;

[0031]

figure 5   shows a schematic illustration of a bent
            reticle for calculating the theoretically
            expected mask bending; and

[0032]

figure 6   shows a schematic illustration for
            quantifying the image field curvature.

DETAILED DESCRIPTION OF PREFERRED EMBODIMENTS

[0033]   Figure 1 schematically shows the essential
component parts of a microlithography projection
exposure apparatus in the form of a wafer scanner 1
provided for the production of large-scale integrated
semiconductor components by means of projection
lithography. The projection exposure apparatus 1
comprises, as light source, an excimer laser (not
shown) having an operating wavelength of 193 nm, other
operating wavelengths, for example 157 nm or 248 nm,
also being possible. A downstream illumination system
3, of which only the light exit region is shown,
generates in its exit surface 4 a large, sharply
delimited illumination field that is illuminated very
homogeneously and is adapted to the telecentric
requirements of the downstream projection objective 5.
The illumination system 3 has devices for selection of
the illumination mode and, in the example, can be
changed over between conventional illumination with a
variable degree of coherence, annular field
illumination and dipole or quadrupole illumination.

- 12 -

[0034]   In   the   direction   of   light   propagation
downstream of the illumination system there is arranged
a   device   40   (reticle   stage)   for   holding   and
manipulating a mask (reticle) 6 such that the latter
5   lies   in   the   object   surface   4   of   the   projection
objective 5 and can be moved in a traveling direction
(scanning direction) 7 (y direction) with the aid of a
scanner drive 41 for scanning operation.

10   [0035]   Downstream of the object surface 4, the
curved form of which will be explained in more detail
with reference to figure 2, there follows at a suitable
distance (object-side operating distance) the reduction
objective 5, which images an image of the mask, with a
15   reduced scale of 4:1, onto a wafer 10 coated with a
photoresist layer. Other reduction scales, e.g. 5:1 or
10:1 or less, are likewise possible. The wafer 10
serving as a light-sensitive substrate is arranged such
that its planar substrate surface 11 with the photo-
20   resist   layer   essentially   coincides   with   the   planar
image plane 12 (depicted in dashed fashion) of the
projection objective 5. The wafer is held by a device
50 (wafer stage) comprising a scanner drive 51 in order
to   move   the   wafer   synchronously   with   the   mask   6
25   parallel to the latter.

[0036]   The projection objective 5 is incorporated
into the wafer scanner such that its optical axis 13 is
oriented vertically and thus parallel to the effective
30   direction g of the force of gravity. The mask mount 40
is designed such that, apart from the force of gravity,
no imposed forces which might lead to a deformation of
the mask 6 occur at the reticle 6 placed on said mount.
Outside   the   region   through   which   the   illumination
35   radiation is to radiate, the transmission mask 6 is
mounted on suitable bearing surfaces (or support
surfaces) which are at a constructionally predetermined
bearing distance from one another (cf. figure 5).

- 13 -

Between the bearing surfaces, the reticle 6 is freely suspended and is exposed to the force of gravity g, which causes a gravitation-dictated mask bending. Depending on the type of reticle and the bearing geometry, a gravitation-dictated bending is established in this case which is always present in essentially the same way as a systematic contribution and, in the case of conventional Petzval-corrected systems, would be converted into a bending of the image of the mask with the square of the imaging ratio. Given a standard size of currently used quartz glass reticles of 6 inches · 6 inches given a typical thickness of 6.35 mm, typical instances of gravitation-dictated bending may be in the range of between 300 and 400 nm depending on the bearing geometry. In the case of typical conventional systems that are optimized for imaging a planar object surface into a planar image surface, this reticle bending, given an imaging scale of 4:1, would lead to an image field curvature of the order of magnitude of between 20 and 25 nm. This indication of the image field curvature relates to the maximum excursion s' of the image field IF in the image field center (at the optical axis OA) in comparison with the axial position of the image field at the edge of the image field, or to a deviation s' - measured in the axially parallel direction - of the curved image field from a plane IM lying perpendicular to the optical axis at the image field edge (cf. figure 6). This image field curvature becomes more critical the smaller the available depth of focus DOF of the projection system. Although it is possible to obtain a good compromise between sagittal and tangential image shell with the aid of manipulators by shifting lenses or displacing them in some other way, this is always accompanied by induced astigmatism on account of the Petzval condition.

[0037]   These problems are avoided in the case of the

- 14 -

embodiment of the projection objective 5 shown. The projection objective 5 is designed for imaging an object surface 4 that is curved convexly with respect to the projection objective (figure 2) into a planar image plane 12. Thus, in contrast to conventional systems, the mutually optically conjugate surfaces do not have the same curvature state or a corresponding curvature state transformed by way of the imaging scale, rather a curvature-altering imaging process is provided. In this case, the projection objective 5 is designed such that all image errors, with the exception of the image field curvature, are completely corrected within narrow tolerances. By contrast, the image field curvature is altered by the projection objective 5 such that a reticle 6 bent with respect to the projection objective can be sharply imaged onto a planar wafer over the entire image surface.

[0038]   The gravitation-dictated bending of the reticle is cylindrical to a first approximation. A complete bias for compensation of this warpage is not possible in a rotationally symmetrical objective design. It can be approximated, however. The situation is different in the case of a scanner objective, that is to say a projection objective provided for use in a wafer scanner. On account of the scanning operation running in the y direction, a rotationally symmetrically curved object surface 4 (figure 2) of the projection objective is translated into an effectively cylindrical object surface 4' of the scanner system (figure 3). This effect results from the fact that only the slotted excerpt 10 which is depicted centrally in figure 2 and corresponds to the illuminated scanner slot is used for imaging. A movement of the approximately cylindrically curved region of the scanner slot in the y direction produces the cylindrically curved effective object surface 4' in figure 3. The curvature thereof is adapted, by the

- 15 -

means for influencing the image field curvature that are provided within the projection objective 5, to the reticle geometry of the bent reticle such that the mask structure to be imaged essentially coincides with the effective cylindrically curved object surface 4, which is optically conjugate with respect to the image plane 12. The mask 6 bent in the direction of the projection objective can thereby be sharply imaged onto the planar wafer 10 over the entire image field diameter. A projection objective designed for an object surface which is curved convexly with respect to the projection objective and which is curved in such a way that the scanner-integrated object surface curvature corresponds to the gravitation-dictated reticle bending will accordingly on average sharply image a bent reticle into a planar image shell. As a result, the gravitation-dictated portion in the focus budget is obviated and a stabler exposure process is possible.

[0039]   Taking account of the reticle bending in the design of the projection objective can also be applied, in principle, to stepper systems. In this case, it is advantageous to generate the intervention in the image field curvature with the aid of nonrotationally symmetrical, for example, toric, surfaces which may be applied on one or more lenses. Suitable aspheric forms are dependent on the bearing geometry of the reticle in this case.

[0040]   In order to explain the required order of magnitude of the image shell overcorrection of the projection objective 5, figure 4 firstly shows, in a perspective illustration, the measured, essentially cylindrically curved profile of the surface of a standard reticle (reticle size 6 · 6 inches, thickness 6.35 mm, material: quartz glass) bent in a gravitation-dictated manner. Figure 5 illustrates the conditions required for deriving the suitable object surface

- 16 -

curvature. The reticle 6 bears on two bearing surfaces 70 which are at a lateral bearing distance LA from one another. The bearing distance is greater than the object field diameter F, in order that the imaging is 5   not disturbed by the bearings. The reticle has a thickness d and is composed of a mask material having density ρ and modulus of elasticity E. Under the action of the force of gravity g, a reticle bending s is established which, in this illustration, is defined as 10   the maximum excursion of the reticle in the g direction with regard to the reference plane 75 which is illustrated in dashed fashion and is defined by the bearing surfaces. A circle arc 4″ which is defined by the bent reticle surface and represents the optimum 15   profile of the curved object surface for this bent reticle corresponds to said bending s. The radius of the circle arc 4″ corresponds to the object surface radius of curvature OFCR of the object surface in this direction running perpendicular to the optical axis. 20

[0041]   Given this schematic geometry of the reticle mount, the theoretically expected bending of the reticle results in accordance with:

25

$$s = \frac{\rho g}{4E} \cdot \frac{LA^4}{d^2} \cdot \frac{F^2}{LA^2}$$

[0042]   An explanation will now be given in connection with figure 6 with regard to the image field curvature to which said bending leads on the image side 30   of the projection objective and what extent of the Petzval correction is necessary for compensation of this effect. In this respect, figure 6 shows the image-side end of the projection objective, together with the region of the image field IF. The object-side reticle 35   bending s is translated into an image-side image field curvature s′ with the square of the imaging scale β in accordance with s′ = $β^2$ · s. In this case, the image

- 17 -

field curvature is parameterized by a deviation s' - measured in the axially parallel direction - of the curved image field IF from a plane IM lying perpendicular to the optical axis OA at the edge of the image field IF. The edge of the image field is at a distance h' (image-side image height) from the optical axis OA. In the sectional plane shown in figure 6, the image field IF is curved spherically to a good approximation, so that it lies on a circle arc having a radius R_P. This is the Petzval radius, for which the following holds true in accordance with the circle equation for long radii to a good approximation: $R_P = h'^2/(2 \cdot s')$. The Petzval sum $1/R_P$ of a system which can image a mask having bending s into a planar image plane thus results from the following equation:

$$1 / R_P = \frac{2 \cdot \beta^2 \cdot s}{h'^2} \, .$$

[0043]   This estimation permits a corresponding bias of the image field curvature to be provided in a projection objective in order to take account of the effects of a gravitation-dictated reticle bending on the imaging quality.

[0044]   A projection objective can be adapted by means of a fixedly predetermined bias to the expected bending of typical reticles. It is also possible to perform a dynamic adaptation by providing suitable manipulators within the projection system in order, upon transition to other types of reticles, by way of example, to be able to perform a changed adaptation without reconstructing the projection objective. Suitable manipulators are, in particular, devices which bring about radii changes and/or refractive index changes within the projection objective. Refractive index changes may be brought about for example by means of pressure changes and/or temperature changes in the

- 18 -

gas in lens interspaces. Radii changes may be introduced by active optical components, e.g. by active mirrors. Heating or cooling a lens may lead to a change in refractive index and dimensioning of the lens and
5 therefore be utilized as a manipulator.

- 19 -

Patent Claims

1.   A projection objective for imaging a pattern
arranged in an object surface of the projection
objective into an image surface of the projection
objective with a demagnified imaging scale, having:
a plurality of optical elements which are arranged
along an optical axis of the projection objective and
are configured in such a way that a defined image field
curvature of the projection objective is set in such a
way that an object surface that is curved convexly with
respect to the projection objective can be imaged into
a planar image surface.

2.   The projection objective as claimed in claim 1,
the object surface being curved in such a way that an
effective object surface curvature in at least one
direction perpendicular to the optical axis essentially
corresponds to a surface curvature which results from a
gravitation-dictated mask bending of the mask.

3.   The projection objective as claimed in claim 1,
the projection objective being designed for use with a
mask that can be moved in a scanning direction, and the
object surface being curved in such a way that an
object surface curvature which is scanner-integrated in
the scanning direction corresponds to the surface
curvature caused by gravitation-dictated bending of the
mask.

4.   The projection objective as claimed in claim 1,
wherein at least one optical element of the projection
objective bears at least one nonrotationally
symmetrical surface.

5.   The projection objective as claimed in claim 4,
the nonrotationally symmetrical surface being a toric

- 20 -

surface   designed   for   influencing   the   image   field
curvature.

6.   The projection objective as claimed in claim 1,
the projection objective essentially being corrected
with regard to all field-dependent image errors, with
the exception of the image field curvature.

7.   The projection objective as claimed in claim 1,
the projection objective essentially being corrected
with regard to all image errors, with the exception of
the image field curvature.

8.   The projection objective as claimed in claim 1,
the projection objective having an image-side numerical
aperture NA > 0.8.

9.   The projection objective as claimed in claim 1,
wherein $\left|R_P\right|$ ≥ 0.1 DOF holds true, where $\left|R_P\right|$ is the
magnitude of the Petzval sum and DOF is the depth of
focus of the projection objective.
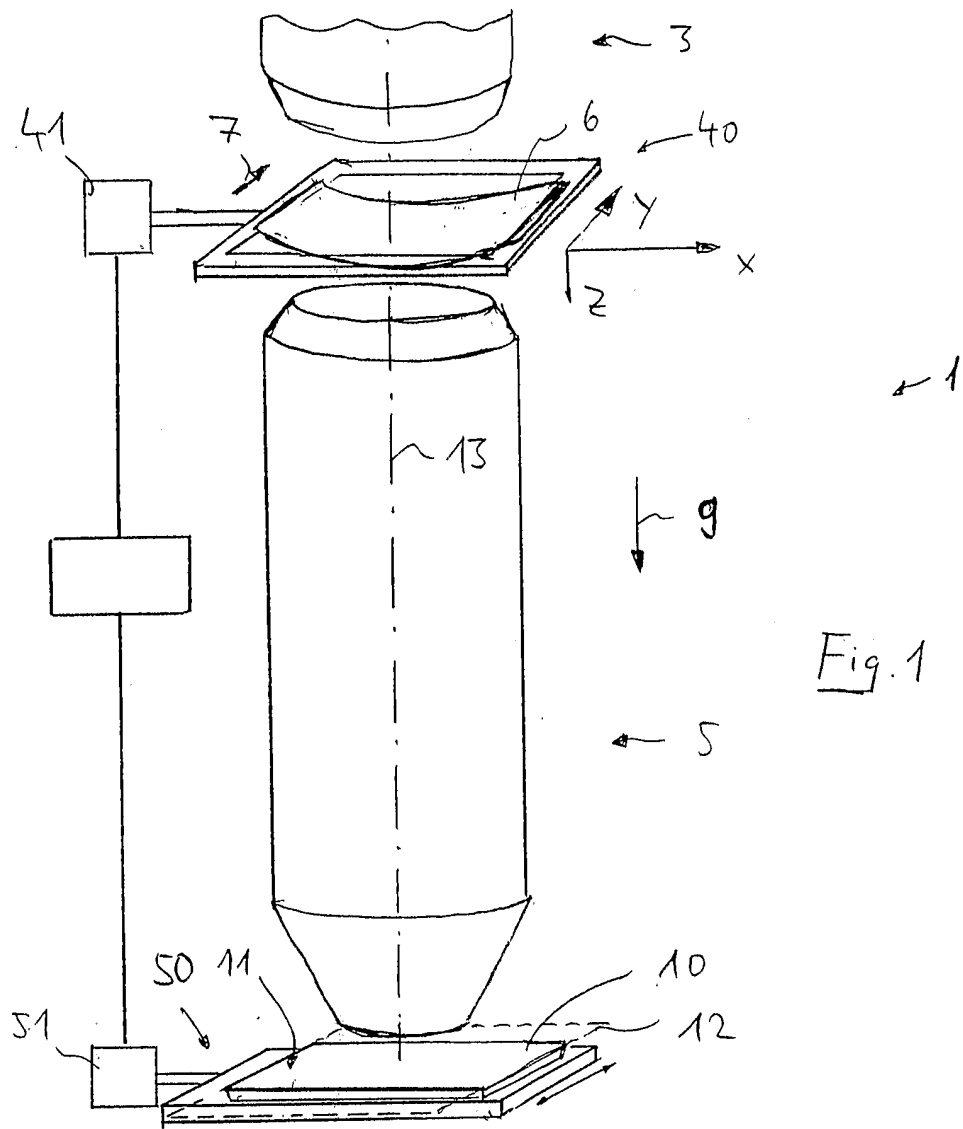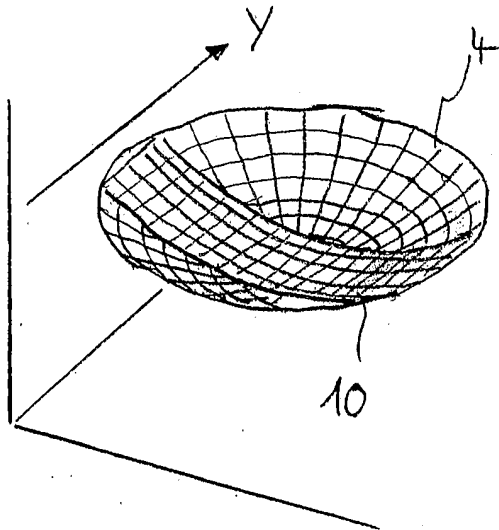
10. A projection objective for imaging a pattern
arranged in an object surface of the projection
objective into an image surface of the projection
objective with a demagnified imaging scale, having:
a plurality of optical elements which are arranged
along an optical axis of the projection objective and
are configured in such a way that a defined image field
curvature of the projection objective is set in such a
way that an object surface that is curved convexly with
respect to the projection objective can be imaged into
a planar image surface, the object surface being curved
in such a way that an effective object surface
curvature in at least one direction perpendicular to
the optical axis essentially corresponds to a surface
curvature which results from a gravitation-dictated

- 21 -

mask bending of the mask, and $\left| R_P \right| \geq 0.1$ DOF holding true, where $\left| R_P \right|$ is the magnitude of the Petzval sum and DOF is the depth of focus of the projection objective.
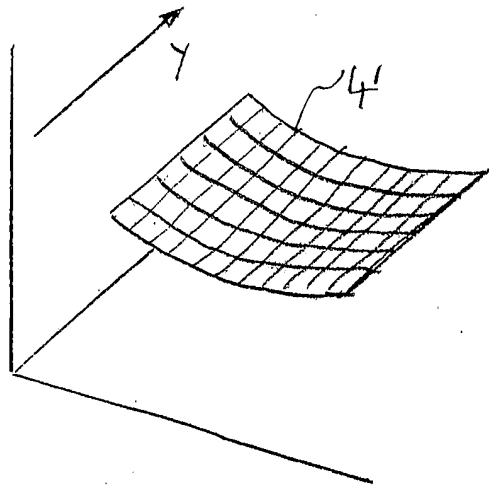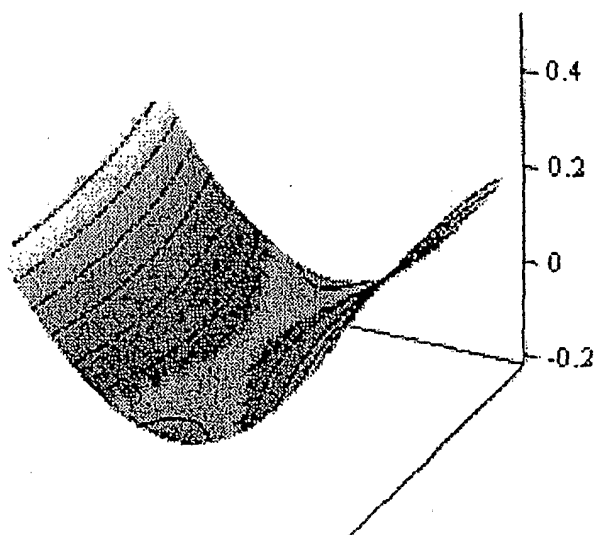
Fig. 1

Fig. 2

Fig. 3

Fig. 4

Fig. 5

Fig. 6