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(54) SUB-RESOLUTION GRATINGS IN EUV IMAGING

(71) Applicants: **IMEC VZW**, Leuven (BE); **Katholieke Universiteit Leuven**, Leuven (BE)

(72) Inventors: **Inhwan Lee**, Leuven (BE); **Joern-Holger Franke**, Auderghem (BE); **Vicky Philipsen**, Tervuren (BE)

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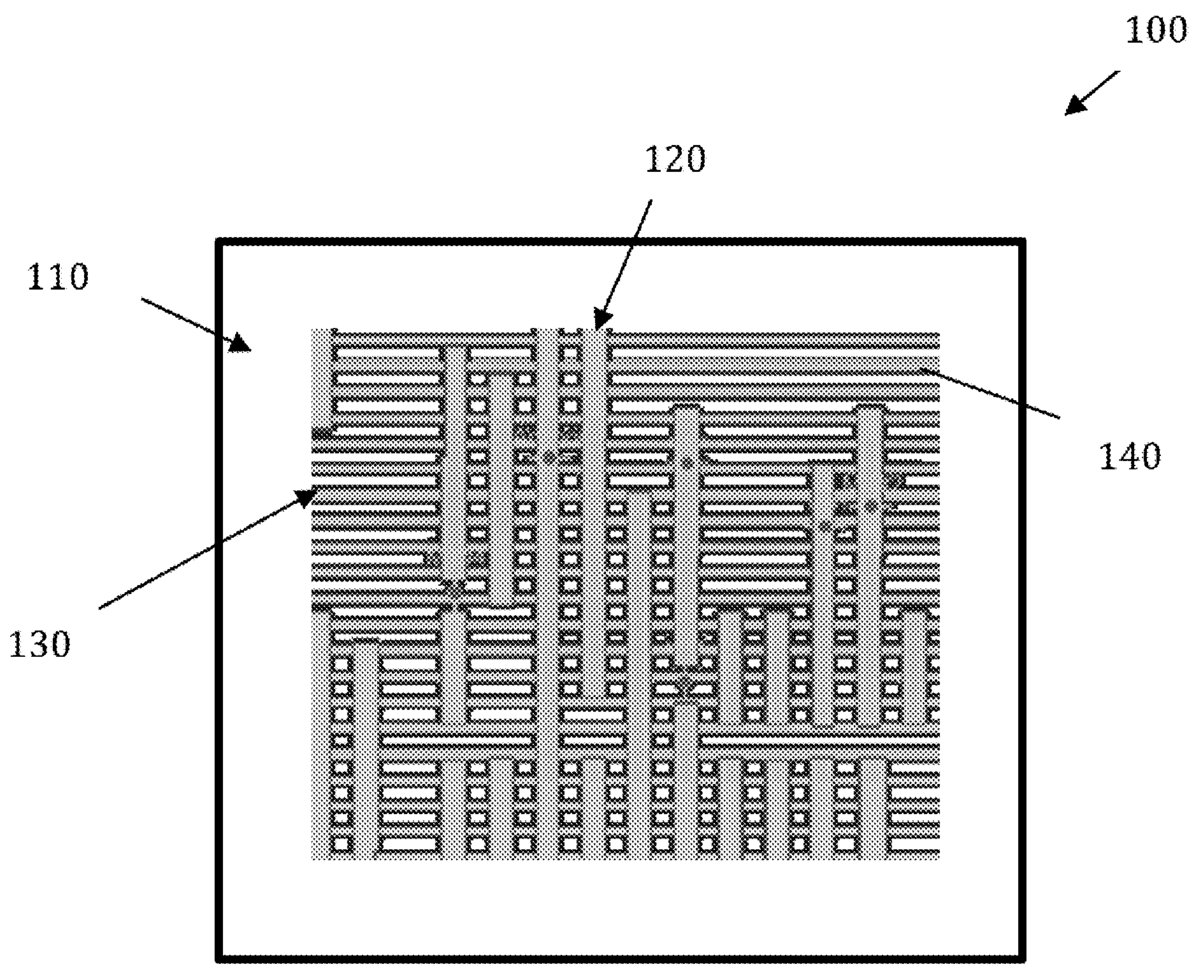
(57) **ABSTRACT**

Example embodiments relate to sub-resolution gratings in extreme ultraviolet (EUV) imaging. One example embodiment includes a mask for EUV lithography processes in a high or hyper numerical aperture range. The mask includes a mask pattern according to a mask layout. The mask layout is a superposition of a first mask sub-layout that includes a plurality of mask features to be printed and a second mask sub-layout that includes one or more sub-resolution gratings having sub-resolution grating lines. The plurality of mask features to be printed includes at least one mask feature oriented along a first direction of the mask layout. The sub-resolution grating lines extend substantially in a second direction of the mask layout and run over substantially a full width in the second direction of the mask layout. The one or more sub-resolution gratings are not printable for the high or hyper numerical aperture range.



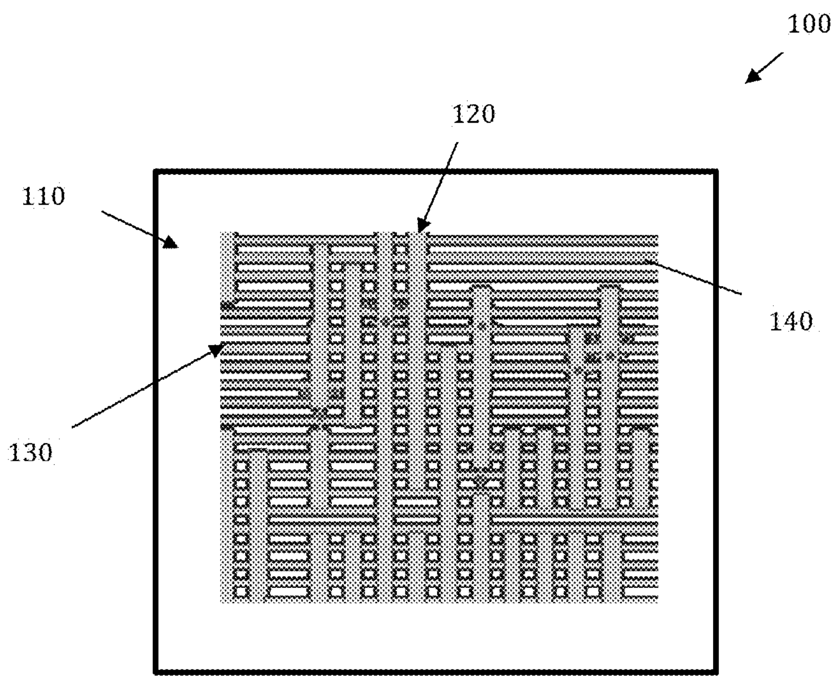


FIG. 1

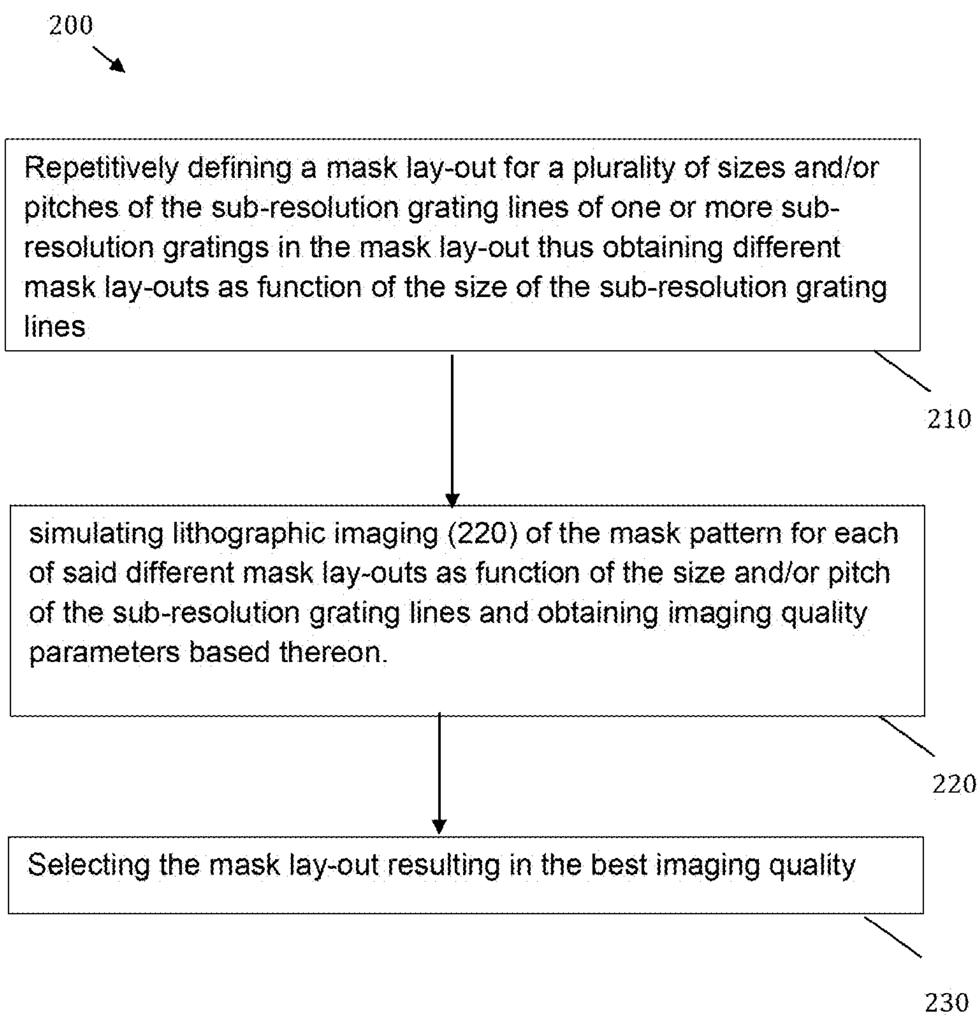

200
Repetitively defining a mask lay-out for a plurality of sizes and/or pitches of the sub-resolution grating lines of one or more sub-resolution gratings in the mask lay-out thus obtaining different mask lay-outs as function of the size of the sub-resolution grating lines
210
simulating lithographic imaging (220) of the mask pattern for each of said different mask lay-outs as function of the size and/or pitch of the sub-resolution grating lines and obtaining imaging quality parameters based thereon.
220
Selecting the mask lay-out resulting in the best imaging quality
230

FIG. 2

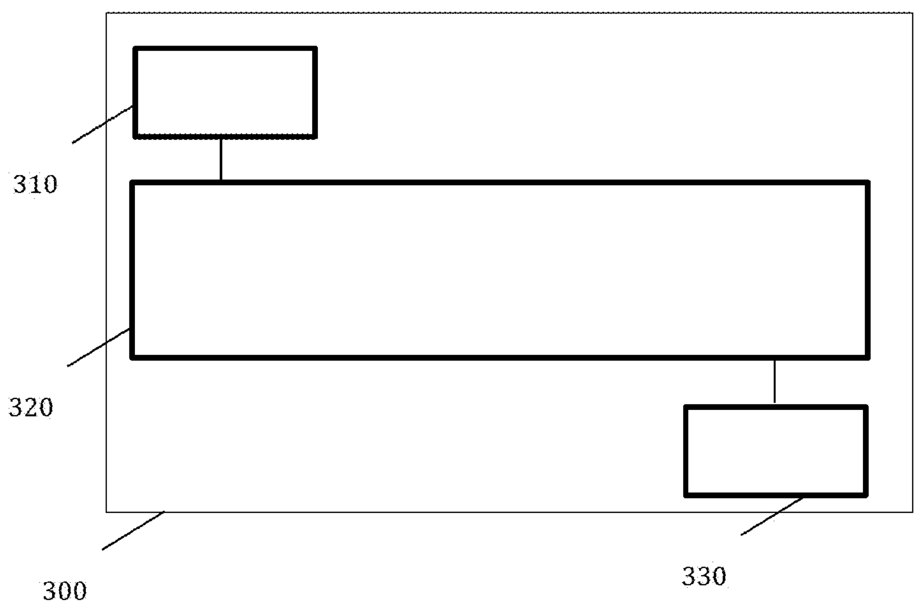


FIG. 3

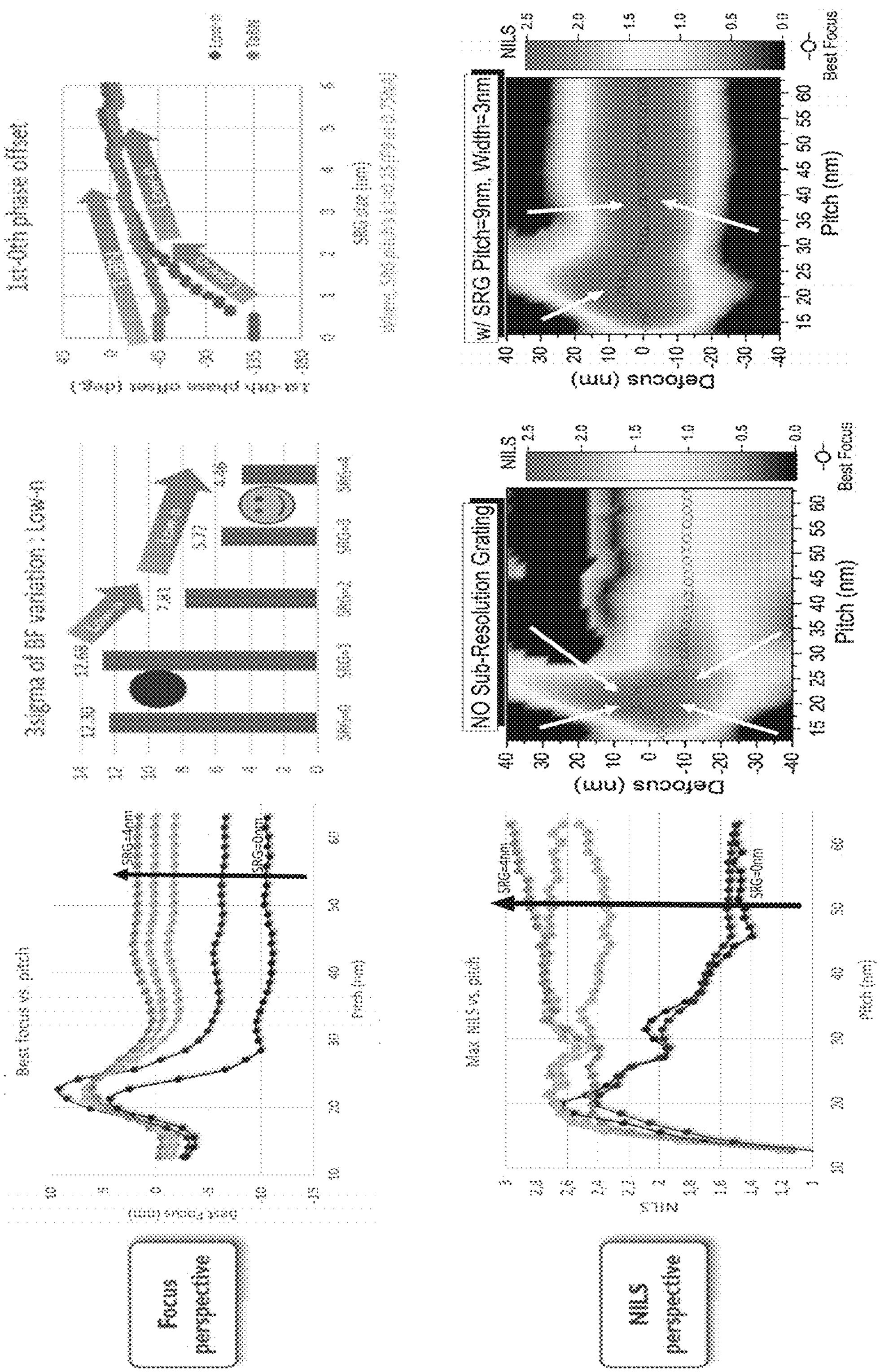

Focus perspective
Best focus vs. pitch
3sigma of BF variation : Low-n
1st-0th phase offset
NILS perspective
Max NILS vs. pitch
NO Sub-Resolution Grating
w/ SRG Pitch=9nm, Width=3nm
Defocus (nm)
Pitch (nm)
NILS
Best Focus

FIG. 4

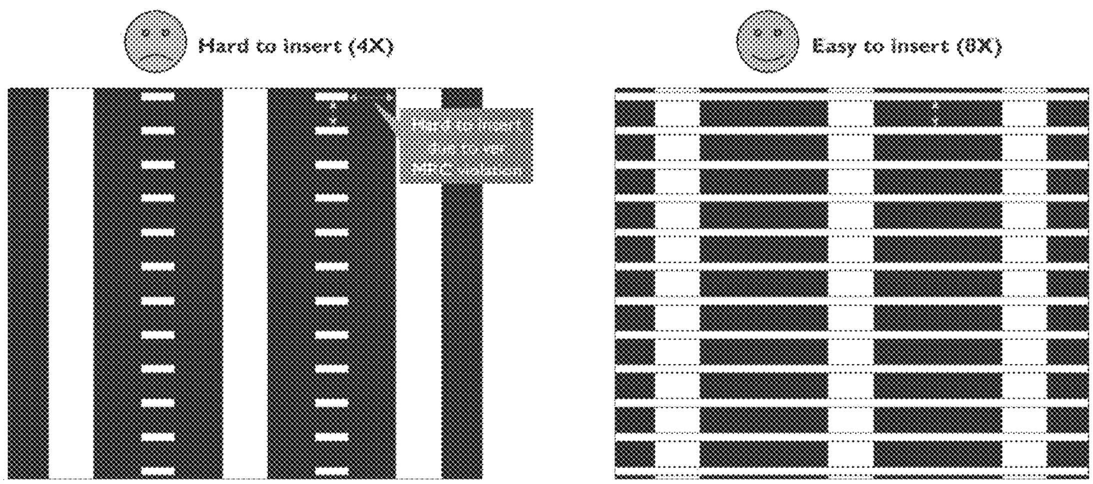

Hard to insert (4X)
Easy to insert (8X)

FIG. 5

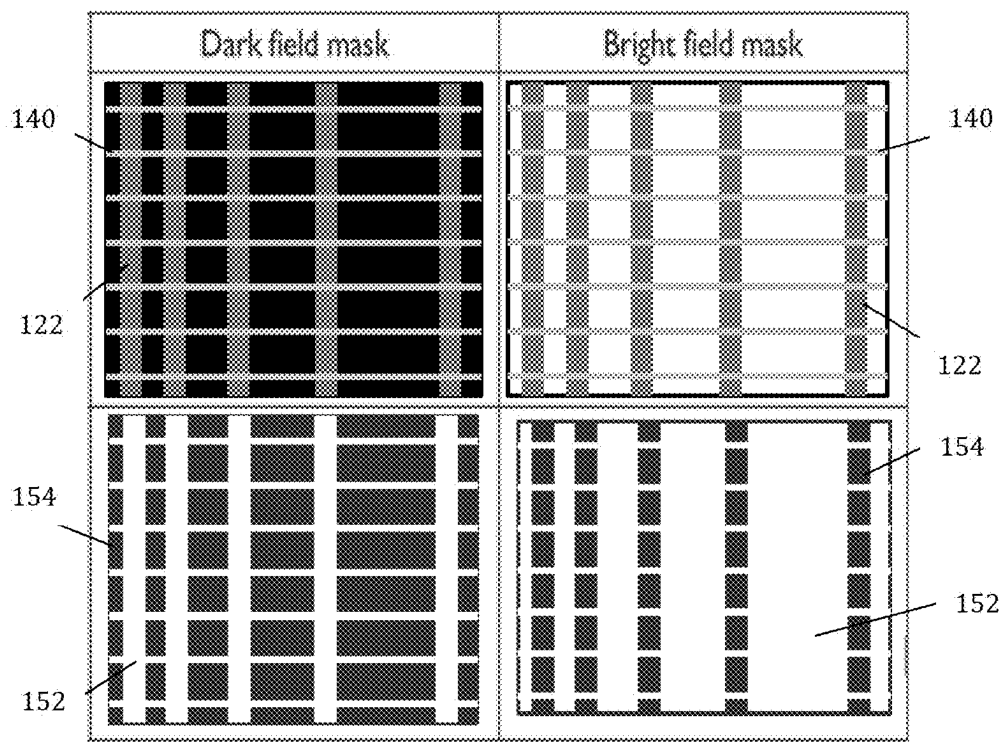

Dark field mask
Bright field mask
140
140
122
122
154
154
152
152

FIG. 6

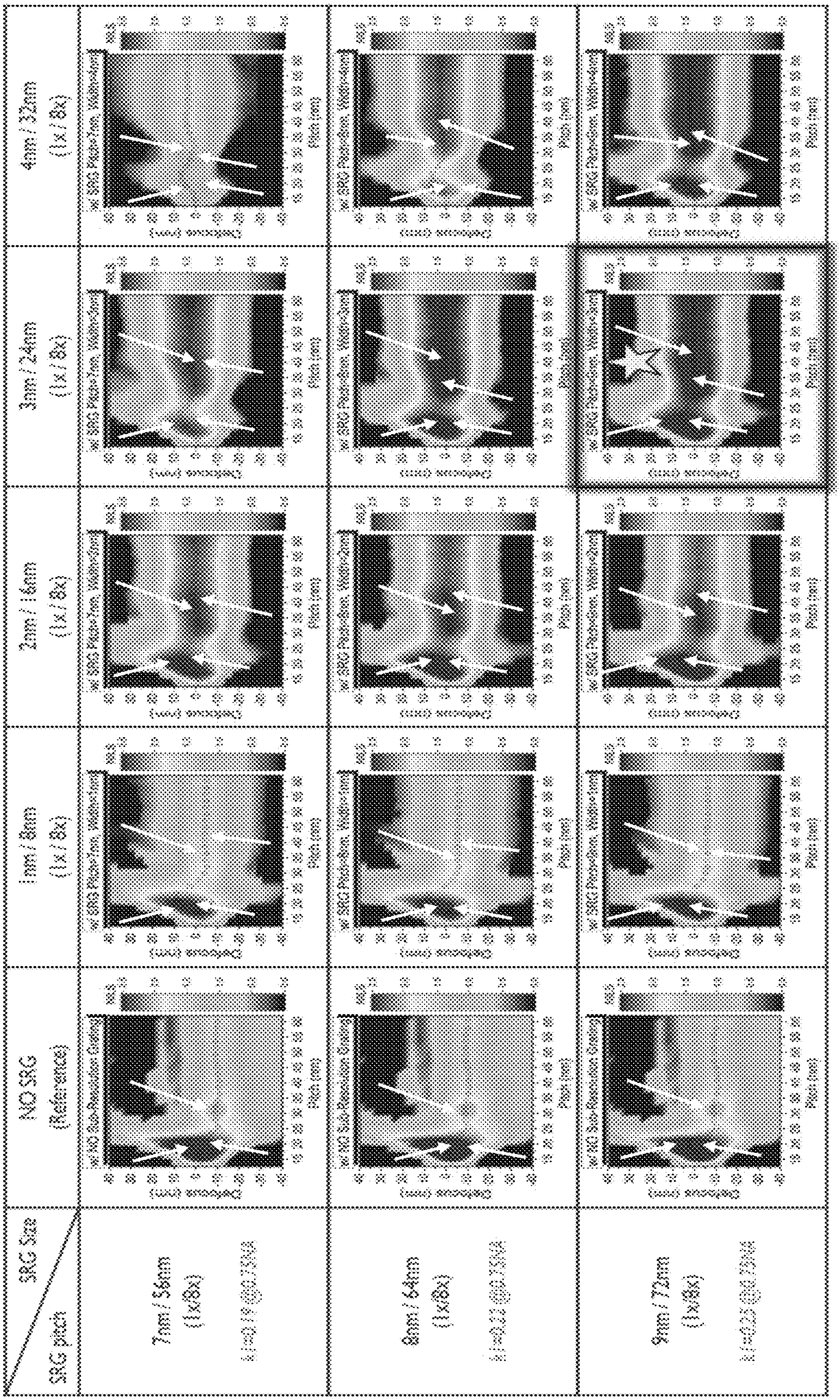

SRG Size
SRG pitch
NO SRG
(Reference)
1nm / 8nm
(1x / 8x)
2nm / 16nm
(1x / 8x)
3nm / 24nm
(1x / 8x)
4nm / 32nm
(1x / 8x)
7nm / 56nm
(1x/8x)
8nm / 64nm
(1x/8x)
9nm / 72nm
(1x/8x)

FIG. 7

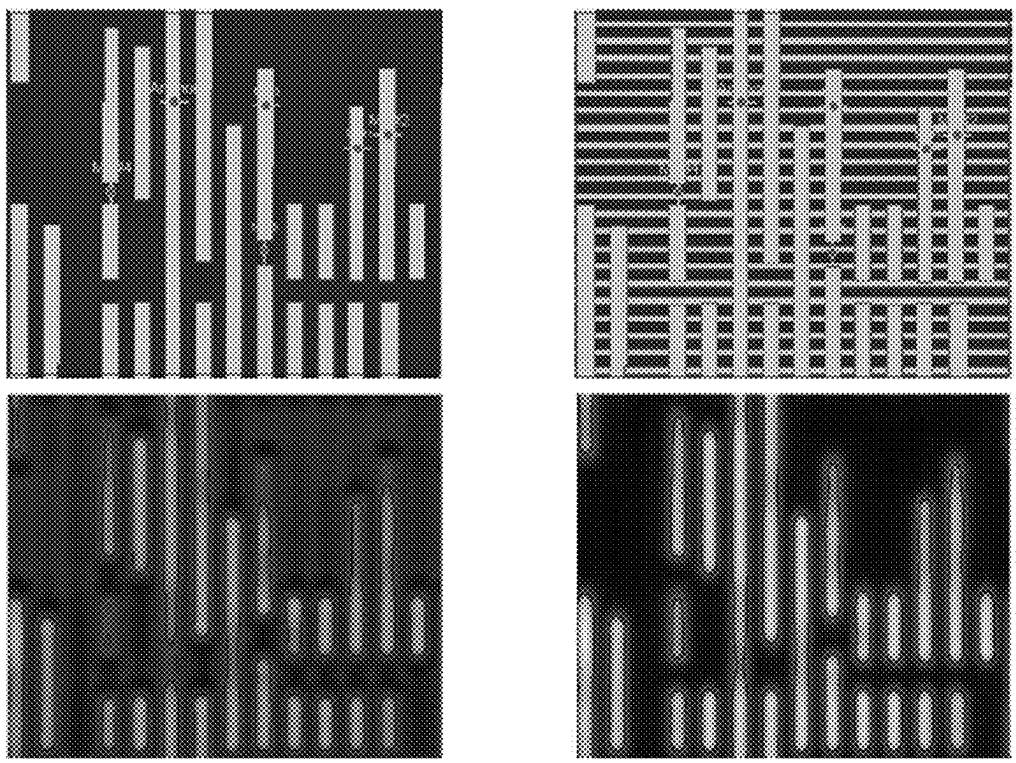


FIG. 8

SUB-RESOLUTION GRATINGS IN EUV IMAGING

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] The present application is a non-provisional patent application claiming priority to European Patent Application No. EP 24158459.8, filed Feb. 19, 2024, the contents of which are hereby incorporated by reference.

FIELD OF THE DISCLOSURE

[0002] The present disclosure relates to the field of extreme ultraviolet imaging and lithography. More particularly, the present disclosure relates to masks, methods for designing masks and methods for performing extreme ultraviolet lithography with these masks.

BACKGROUND

[0003] The field of semiconductor manufacturing has seen remarkable advancements over the past decades, with the miniaturization of electronic components being a key driver of technological progress. One of the critical steps in semiconductor fabrication is the process of lithography, which involves transferring intricate patterns onto a silicon wafer to define the various features of integrated circuits. As the demand for smaller and more powerful electronic devices continues to grow, the semiconductor industry is constantly seeking ways to print ever smaller features at high contrast.

[0004] Projection lithography technology has been at the forefront of this endeavour, evolving to utilize shorter wavelength light and larger numerical aperture (NA) optics to achieve finer resolution. The introduction of Extreme Ultraviolet (EUV) lithography, with its 13.5 nm wavelength, marked a significant leap forward in this respect. However, the quest for even greater resolution has led to the exploration of increasing the NA further. This presents a challenge, as the depth of focus (DoF) is inversely proportional to the square of the NA. Consequently, in high NA (0.55) and hyper NA (larger than 0.75) EUV lithography systems, the DoF becomes extremely limited.

[0005] In EUV lithography, the pattern to be printed on the wafer is encoded on a photomask. Due to the optical properties at EUV wavelengths, the structures on the mask may be multiples of the wavelength thick, resulting in a three-dimensional mask topology. This complexity leads to variations in the optimal focus position for different pattern pitches on the mask. As all pitches may be printed simultaneously, some will inevitably be out of focus, which is exacerbated as the NA increases.

[0006] The industry has explored various techniques to address the imaging issues induced by mask three-dimensionality (M3D) in EUV lithography. One common approach is the use of sub-resolution assist features (SRAFs), which are small lines placed parallel to the main features to improve focus variation through pitch and increase normalized image log slope (NILS). However, the placement of SRAFs may be complex and/or require specialized tools. Moreover, SRAFs can sometimes print unintentionally, leading to defects and increased stochastic failure rates.

[0007] Another approach to reduce best focus shifts is to alter the mask material. Low refractive index (low-n) absorber materials with modest absorption have been considered for their potential benefits, including increased reflectivity and diffraction efficiency, which can lead to sharper images. However, these materials also introduce new challenges, such as a drift in best focus for larger pitches, which can sometimes worsen the overall focus range compared to standard mask materials.

[0008] Despite these efforts, the industry continues to face significant challenges in EUV mask technology. The variations in best focus across different pitches and the quest for higher NILS remain critical issues that need to be addressed. As the semiconductor industry pushes the boundaries of what is possible with EUV lithography, there is a clear and ongoing need for further advancements in mask technology to overcome these challenges and enable the continued scaling of electronic devices.

SUMMARY

[0009] Example embodiments may improve the overall process window for multiple features when using imaging using a numerical aperture of 0.55 or higher.

[0010] Example embodiments may obtain aligned best focus through pitch and better image contrast through pitch for EUV lithography.

[0011] Example embodiments may be compatible with any kind of mask. When mask absorber stacks are used, the reflectivity of the absorber stacks may be selected such that the sub-resolution patterns of manufacturable size lead to appropriate background intensity of the absorber patterned with sub-resolution features.

[0012] The above is accomplished by a method and apparatus according to example embodiments.

[0013] In the first aspect, the disclosure relates to a mask for EUV lithography processes in a high or hyper numerical aperture range, the mask comprising a mask pattern according to a mask layout being the superposition of a first mask sub-layout comprising a plurality of mask features to be printed, the plurality of mask features to be printed comprising at least one mask feature oriented along a first direction of the mask layout, and a second mask sub-layout comprising one or more sub-resolution gratings having sub-resolution grating lines, the sub-resolution grating lines extending substantially in a second direction of the mask layout and running over substantially the full width in the second direction of the mask layout, the one or more sub-resolution gratings not being printable for the high or hyper numerical aperture range.

[0014] The sub-resolution grating pitch (SRGpitch) for the one or more sub-resolution gratings (SRGs) may be selected to be out of the resolution limit of the EUV lithography processes. The sub-resolution gratings thus do not interfere with the intended mask pattern by remaining unprinted.

[0015] The size for the sub-resolution grating lines may be selected based on best focus. This allows optimizing the focus across various pitches, thereby improving the overall quality of the lithography process. The size for the sub-resolution grating lines may also be selected based on highest contrast. This can allow for enhancing the image contrast.

[0016] The sub-resolution grating pitch of the one or more sub-resolution gratings may be selected based on depth of focus through pitch for patterns to be printed. The sub-resolution grating pitch of the one or more sub-resolution gratings may also be selected based on highest contrast through pitch for patterns to be printed. This allows achieving high contrast across various pitches for patterns to be printed.

[0017] The combination of the sub-resolution grating pitch and size of the sub-resolution grating lines of the one or more sub-resolution gratings thus may be selected based on best depth of focus through pitch and/or highest contrast through pitch for patterns to be printed.

[0018] The second mask sub-layout may comprise no sub-resolution grating at a position of gaps between the plurality of mask features in the first sub-layout.

[0019] The first direction may in some embodiments be the same as the second direction.

[0020] In some embodiments, the first direction may be different from the second direction.

[0021] The grating lines may cross substantially all mask features.

[0022] In embodiments, the first direction may be perpendicular to the second direction.

[0023] In embodiments, the mask may be for use in a EUV lithography tool using an anamorphic optics system in which demagnification for an X-direction is smaller than demagnification in the Y direction. The first direction along which the plurality of mask features are extending may correspond with the Y direction and the second direction may correspond with the X direction.

[0024] Example embodiments may be compatible with various shapes of illumination sources used in EUV scanners or lithography.

[0025] Example embodiments may use sub-resolution gratings to stabilize the 0th order phase through pitch for patterns to be printed.

[0026] In some embodiments, by using sub-resolution gratings, the image contrast (e.g., the NILS which is a metric for the image contrast) may be substantially uniformly high in all pitch regions for patterns to be printed. Such a NILS is not obtained without the use of sub-resolution gratings. Although a slight reduction in NILS can be seen at small pitch, overall the NILS is far more substantially uniform and high in all pitch regions for patterns to be printed.

[0027] Some embodiments can be immediately applicable for high-numerical aperture lithography for currently manufacturable dimensions.

[0028] Some embodiments can be applied for the manufacturing of e.g. 2D metal patterns of logic, as well as for 1D metal designs containing L/S and line ends or 1.5D Metal designs containing landing pads.

[0029] Some embodiments can be applied for imaging of 2D geometries like contact holes or logic via layers.

[0030] Some embodiments can enhance depth-of-focus by reducing the complexity of the best focus problem that often dominates source choice. Some embodiments may assist in improving the depth of focus, which is a critical element when using e.g. hyper numerical aperture lithography.

[0031] Some embodiments may be combinable with other techniques such as fading correction, thus allowing further optimization of the imaging and of the mask stack used at the same time.

[0032] Example embodiments may allow mask types to be used with a highly reflective absorber, whereby the best focus shift for isolated features is mitigated with the SRGs and whereby pole-to-pole offset is mitigated via fading correction. In this way one could optimize for aligned best focus, high NILS for all features and e.g., high total reflectivity as well as low intensity in the dark region.

[0033] Example embodiments may allow for the use of sub resolution gratings that result in an overall brighter mask.

[0034] In the second aspect, the disclosure relates to a computer-implemented method for designing a mask layout for EUV lithography processes in a high or hyper numerical aperture range, the method comprising defining a mask layout for the mask pattern as a superposition of a first mask sub-layout comprising a plurality of mask features to be printed, the plurality of mask features to be printed comprising at least one mask feature oriented along a first direction of the mask layout, and a second mask sub-layout comprising one or more sub-resolution gratings having sub-resolution grating lines, the sub-resolution grating lines extending substantially in a second direction of the mask layout, and running over substantially the full width in the second direction of the mask layout, the one or more sub-resolution gratings being not printable for the high or hyper numerical aperture range.

[0035] In embodiments, the method may comprise repeating the defining of a mask layout for a plurality of sub-resolution grating pitches and/or sizes of the sub-resolution grating lines of the one or more sub-resolution gratings thus obtaining different mask layouts as function of the size of the sub-resolution grating lines, simulating lithographic imaging of the mask pattern for each of the different mask layouts as function of the sub-resolution pitch and the size of the sub-resolution grating lines thus obtaining imaging quality parameters, and selecting the mask layout having the best imaging quality parameters. The imaging quality parameters may for example be depth of focus through pitch and/or highest contrast through pitch for the patterns to be printed. This embodiment may enable the selection of an optimized mask layout through simulation, which can lead to improved lithographic results.

[0036] The method may further comprise simulating lithographic imaging as function of multiple monopole exposure passes or injected aberrations. This embodiment may account for various lithographic conditions, which can lead to a more robust and reliable mask design.

[0037] In a third aspect, the present disclosure relates to a system for determining lithographic processing conditions for EUV lithography processes in a high or hyper numerical aperture range, the system comprising an input for obtaining characteristics of an illumination source and of a lithography pattern to be created, and a processor programmed for defining a mask layout for the mask pattern as a superposition of a first mask sub-layout comprising a plurality of mask features to be printed, the plurality of mask features to be printed comprising at least one mask feature oriented along a first direction of the mask layout, and a second mask sub-layout comprising one or more sub-resolution gratings having sub-resolution grating lines, the sub-resolution grating lines extending substantially in a second direction of the mask layout and running over substantially the full width in the second direction of the mask layout, the sub-resolution grating further not being printable for the high or hyper numerical aperture range. The system may further include an output system for outputting the designed or selected mask layout.

[0038] The processor may furthermore be programmed for repeating the defining of a mask layout for a plurality of sub-resolution grating pitches and/or sizes of the sub-resolution grating lines thus obtaining different mask layouts as function of the sub-resolution grating pitch and as function of the size of the sub-resolution grating lines, simulating lithographic imaging of the mask pattern for each of the different mask layouts as function of the sub-resolution grating pitch and the size of the sub-resolution grating lines thus obtaining imaging quality parameters, and selecting the mask layout having the best imaging quality parameters. The imaging quality parameters may for example be depth of focus through pitch and/or highest contrast through pitch for the patterns to be printed.

[0039] The system may be implemented as a computer program product for, when executing on a processor, carrying out one of the methods according to the second aspect of the disclosure.

[0040] In a further aspect, the present disclosure relates to a data carrier storing a computer program product, when executed on a processor, carrying out one of the method according to the second aspect of the disclosure.

[0041] Particular aspects of the disclosure are set out in the accompanying independent and dependent claims. Features from the dependent claims may be combined with features of the independent claims and with features of other dependent claims as appropriate and not merely as explicitly set out in the claims.

[0042] Although there has been constant improvement, change and evolution of devices in this field, the present concepts are believed to represent substantial new and novel improvements, including departures from prior practices, resulting in the provision of more efficient, stable and reliable devices of this nature.

[0043] The above and other characteristics and features will become apparent from the following detailed description, taken in conjunction with the accompanying drawings. This description is given for the sake of example only, without limiting the scope of the disclosure. The reference figures quoted below refer to the attached drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

[0044] FIG. **1** is a schematic representation of a mask for EUV lithography processes, according to example embodiments.

[0045] FIG. **2** is a flow diagram of a computer-implemented method for designing a mask layout for EUV lithography processes, according to example embodiments.

[0046] FIG. **3** is a system for designing a mask layout for EUV lithography processes, according to example embodiments.

[0047] FIG. **4** illustrates an example of the use of a sub-resolution grating in a mask layout for obtaining improved EUV lithography masks, according to example embodiments.

[0048] FIG. **5** illustrates an example of the use of a sub-resolution grating in a mask layout for obtaining improved EUV lithography masks, according to example embodiments.

[0049] FIG. **6** illustrates an example of the use of a sub-resolution grating in a mask layout for obtaining improved EUV lithography masks, according to example embodiments.

[0050] FIG. **7** illustrates an example of the use of a sub-resolution grating in a mask layout for obtaining improved EUV lithography masks, according to example embodiments.

[0051] FIG. **8** illustrates an example of the use of a sub-resolution grating in a mask layout for obtaining improved EUV lithography masks, according to example embodiments.

[0052] In the different drawings, the same reference signs refer to the same or analogous elements.

DETAILED DESCRIPTION

[0053] Particular embodiments will be described with reference to certain drawings, but the disclosure is not limited thereto. The drawings described are only schematic and are non-limiting. In the drawings, the size of some of the elements may be exaggerated and not drawn on scale for illustrative purposes. The dimensions and the relative dimensions do not necessarily correspond to actual reductions to practice.

[0054] The terms first, second, third and the like in the description and in the claims, are used for distinguishing between similar elements and not necessarily for describing a sequence, either temporally, spatially, in ranking or in any other manner. It is to be understood that the terms so used are interchangeable under appropriate circumstances and that the embodiments described herein are capable of operation in other sequences than described or illustrated herein.

[0055] Moreover, the terms top and over and the like in the description and the claims are used for descriptive purposes and not necessarily for describing relative positions. It is to be understood that the terms so used are interchangeable under appropriate circumstances and that the embodiments described herein are capable of operation in other orientations than described or illustrated herein.

[0056] It is to be noticed that the term "comprising," also used in the claims, should not be interpreted as being restricted to the components listed thereafter; it does not exclude other elements or steps. It is thus to be interpreted as specifying the presence of the stated features, integers, steps or components as referred to, but does not preclude the presence or addition of one or more other features, integers, steps or components, or groups thereof. Thus, the scope of the expression "a device comprising A and B" should not be interpreted as being limited to devices consisting only of components A and B. It means that the only relevant components of the device are A and B. The term "comprising" therefore covers the situation where only the stated features are present and the situation where these features and one or more other features are present. The word "comprising" therefore also includes as one embodiment that no further components are present. When the word "comprising" is used to describe an embodiment in this application, it is to be understood that an alternative version of the same embodiment, wherein the term "comprising" is replaced by "consisting of," is also encompassed within the scope of the present disclosure.

[0057] Reference throughout this specification to "one embodiment" or "an embodiment" means that a particular feature, structure or characteristic described in connection with the embodiment is included in at least one embodiment. Thus, appearances of the phrases "in one embodiment" or "in an embodiment" in various places throughout this specification are not necessarily all referring to the same embodiment, but may. Furthermore, the particular features, structures or characteristics may be combined in any suitable manner, as would be apparent to one of ordinary skill in the art from this disclosure, in one or more embodiments.

[0058] Similarly it should be appreciated that in the description of example embodiments, various features are sometimes grouped together in a single embodiment, figure, or description thereof for the purpose of streamlining the disclosure and aiding in the understanding of one or more of the various aspects. This method of disclosure, however, is not to be interpreted as reflecting an intention that the claimed invention requires more features than are expressly recited in each claim. Rather, as the following claims reflect, various aspects lie in less than all features of a single foregoing disclosed embodiment. Thus, the claims following the detailed description are hereby expressly incorporated into this detailed description, with each claim standing on its own as a separate embodiment.

[0059] Furthermore, while some embodiments described herein include some but not other features included in other embodiments, combinations of features of different embodiments are meant to be within the scope of the disclosure, and form different embodiments, as would be understood by those in the art. For example, in the following claims, any of the claimed embodiments can be used in any combination.

[0060] Furthermore, some of the embodiments are described herein as a method or combination of elements of a method that can be implemented by a processor of a computer system or by other means of carrying out the function. Thus, a processor with the necessary instructions for carrying out such a method or element of a method forms a means for carrying out the method or element of a method. Furthermore, an element described herein of an apparatus embodiment is an example of a means for carrying out the function performed by the element for the purpose of carrying out various embodiments.

[0061] In the description provided herein, numerous specific details are set forth. However, it is understood that embodiments may be practiced without these specific details. In other instances, well-known methods, structures and techniques have not been shown in detail in order not to obscure an understanding of this description.

[0062] The following terms are provided solely to aid in the understanding of example embodiments.

[0063] Where reference is made to "a mask for EUV lithography processes," reference is made to a photomask specifically designed for use in extreme ultraviolet (EUV) lithography systems that operate with a high or hyper numerical aperture (NA). Where reference is made to high numerical aperture (NA), reference is made to a numerical aperture of more than 0.5. Where reference is made to hyper numerical aperture, reference is made to a numerical aperture of more than 0.55.

[0064] Where reference is made to "pitch for the one or more sub-resolution gratings" or sub-resolution grating pitch, this refers to the distance between the centers of adjacent lines or features within the sub-resolution grating pattern. The sub-resolution grating pitch is selected to be beyond the resolution capability of the EUV lithography process, meaning that the individual lines or features of the grating will not be distinctly printed on the substrate. Examples of specific embodiments include sub-resolution grating pitches that are greater than the minimum feature size that the lithography system can resolve, which may vary depending on the specific capabilities of the EUV lithography equipment being used.

[0065] Where reference is made to "pole-to-pole offset," reference is made to the technique whereby the pattern shift resulting from illumination from different illumination poles is used for pushing the resolution limit.

[0066] As used herein, and unless otherwise specified, the term "size for the sub-resolution grating lines" refers to the width or critical dimension of the individual lines or features that make up the sub-resolution grating pattern on the mask.

[0067] Several embodiments will now be described. It is clear that other embodiments can be configured according to the knowledge of persons skilled in the art without departing from the technical teaching of the disclosure, the disclosure being limited only by the terms of the appended claims.

[0068] In a first aspect, the present disclosure relates to a mask for EUV lithography processes in a high or hyper numerical aperture range. Whereas masks for EUV lithography may be used at one specific numerical aperture and thus are designed therefore, masks as referred to in the present disclosure could be made hybrid, i.e. for use in different tools having different NA. In such cases, the frames of the mask could for example comprise different alignment marks for different NA tools.

[0069] The mask according to some embodiments can be any type of EUV lithography mask. It may be a bright field mask or a dark field mask. The mask may be made of any suitable material. In some embodiments, the mask may be made of low-n material, but embodiments are not limited thereto.

[0070] The mask manufacturing that will be formed based on the determined mask design can be any conventional EUV mask manufacturing technology. The mask may be made using e-beam writing technology. The mask features and the one or more sub-resolution gratings that will be defined below could in some embodiments be implemented in multiple processing steps or simultaneously, e.g. implementing e-beam writing and etching.

[0071] The mask comprises a mask pattern, which may be a pattern formed by mask material on a substrate. The mask pattern thereby is made according to a mask layout.

[0072] According to some embodiments, the mask layout is a superposition of a first mask sub-layout and a second mask sub-layout.

[0073] In other words, the mask layout is the result of overlaying or combining multiple individual patterns or sub-layouts. The first mask sub-layout comprises a plurality of mask features to be printed. This plurality of mask features to be printed comprises at least one mask feature oriented along a first direction of the mask layout. This refers to the portion of the mask pattern that includes the primary features intended to be transferred onto the wafer or substrate during the lithography process. These features represent the actual patterns or device structures that may be used for the final manufactured product. Examples of specific embodiments include, but are not limited to, lines, spaces, contact holes, and other geometric shapes that correspond to the elements of an integrated circuit or other devices.

[0074] The second mask sub-layout comprises one or more sub-resolution gratings having sub-resolution grating lines. The one or more sub-resolution gratings may have a different sub-resolution grating pitch or the same sub-resolution grating pitch. If different sub-resolution grating pitches are used for different sub-resolution gratings, optimization may be performed for each of them. The sub-resolution grating lines of the one or more sub-resolution gratings extend substantially in a second direction of the mask layout and run over substantially the full width in the second direction of the mask layout. The one or more sub-resolution gratings are not printable for the high or hyper numerical aperture range for which the mask is used. The sub-resolution grating lines thus only include grating lines with dimensions below the resolution limit of the lithography system, such that they do not print as distinct features on the wafer.

[0075] The resulting mask layout that is used for manufacturing the corresponding mask, may in a final representation be a binary representation, i.e. the combination of mask features and sub-resolution grating lines being expressed only as 0 and 1. Here, 0 represents a dark area (=absorbing area) where light is absorbed, and 1 represents a bright area (=reflecting area) where light is reflected.

[0076] FIG. **1** illustrates a mask layout **110**, by way of illustration shown as the corresponding pattern on a substrate resulting in a mask **100**. In FIG. **1**, the mask layout **110** is a superposition of a first mask sub-layout **120** comprising the mask features intended for printing, and a second mask layout **130** comprising one or more sub-resolution gratings **140**, not intended for occurring as printed features in the final substrate.

[0077] In some embodiments, the first direction may be the same as the second direction. One example of such an embodiment is wherein horizontal metal designs at a pitch of 20 nm are combined with a sub-resolution grating having sub-resolution grating lines at a sub-resolution grating pitch of 10 nm. Some embodiments may address the 2-bar critical dimension asymmetry through focus occurring for horizontal metal design (lines extending along the X direction) by using manufacturable sub-resolution gratings extending along X direction in cases where sub-resolution gratings extending along Y direction would not be manufacturable.

[0078] In some embodiments, the first direction may be different from the second direction. This covers for example the case where the pattern design to be printed is rotated with respect to the direction of the sub-resolution grating direction.

[0079] In some embodiments, the first and the second direction may be perpendicular to each other. In such embodiments, particular aspects of EUV lithography may be utilized. In EUV lithography, increasing the NA implies that the angles at which the radiation hits the mask increase resulting in a loss of reflectivity in which leads to printing issues. This issue has been addressed in the field by the use of anamorphic optics. Rather than uniformly shrinking the pattern to be printed, the reflective optics of the EUV system used demagnifies the pattern to be printed differently in one direction compared to the direction perpendicular thereto. A demagnification in EUV lithography systems used is a demagnification for an X-direction being smaller than the demagnification in the Y direction. An example of such a system includes a demagnification in X-direction being 4× and a demagnification in Y-direction being 8×.

[0080] Since the scale of the mask is relatively large for the Y direction, it allows for a relaxed and design friendly layout. Making use of this anamorphic optics design system, in some embodiments the sub-resolution grating lines can be easily inserted with its pitch in the Y direction (i.e., lines extending along the X direction) without the risk of violation of the mask rule checks (MRC). It does not cause the unwanted printability issue of sub-resolution features because it uses patterns outside the resolution limit. Consequently, in some embodiments, the first direction along which the plurality of mask features are extending corresponds with the Y direction and the second direction corresponds with the X direction.

[0081] In some embodiments, the mask's design is further tuned by selecting the sub-resolution grating pitch and size of the sub-resolution grating lines based on factors such as best focus, highest contrast, and depth of focus through pitch for patterns to be printed. These selections allow for optimization of the lithography process, as they enhance image quality and uniformity across various pitches. According to some specific embodiments, the size of the grating lines of the one or more sub-resolution gratings is selected based on best imaging performance. This can vary on the mask tonality and mask stack (absorber thickness, absorber material's refractive indices). The sub-resolution grating pitch of the one or more sub-resolution gratings is selected to be out of resolution limit, which guarantees that there is no risk of unwanted sub features printability on the wafer. It furthermore takes into account the mask manufacturing feasibility. The sub-resolution grating pitch can be further relaxed or fine-tuned if the maximum sigma-y point of illumination pupil can be reduced to a smaller value.

[0082] By way of illustration, the disclosure not being limited thereto, the allowable sub-resolution grating pitch can be expressed as

$$\frac{\lambda}{NA * (1 + \sigma_{Ymax})} > \text{pitch}_{sub-resolution\ grating}$$

[0083] where λ is the wavelength of the EUV lithography processes and σ_{Ymax} is the maximum sigma-y point of the illumination pupil. If for example the maximum sigma-y point of the illumination pupil σ_{Ymax} is 0.8, the minimal pitch can be 10 nm, whereas if the maximum sigma-y point of the illumination pupil σ_{Ymax} is 1, the minimal pitch can be 9 nm. If the current achievable minimum width that can be drawn on the mask using e-beam writing technology is 24 nm to 32 nm, this could result—in an image scale with 8× magnification—in 3-4 nm. For 0.55NA, the resolution limit then is 12.3 nm pitch at wafer scale, so 98.2 nm at mask scale in the Y direction. For 0.75NA, the resolution limit is 9 nm pitch at wafer scale, 72 nm at mask scale in the Y direction. Printable features on mask are therefore much smaller than the smallest periodicity that could potentially be imaged by the high-NA or hyper-NA tools, especially if the grating is oriented as horizontal lines (which are magnified by 8×).

[0084] According to some embodiments, sub-resolution gratings having grating lines running over substantially the full width of the mask are implemented in some areas of the mask, but no sub-resolution gratings are provided in areas where gaps exist between mask features to be printed, simplifying the design where gratings are unnecessary.

[0085] In a second aspect, the present disclosure relates to a computer-implemented method for designing a mask layout for EUV lithography processes in a high or hyper numerical aperture range. The method may result in a mask for EUV lithography processing as described in the first aspect. According to some embodiments, the method comprises defining a mask layout for the mask pattern as a superposition of a first mask sub-layout and a second mask sub-layout. The first mask sub-layout comprises a plurality of mask features to be printed, the plurality of mask features to be printed comprising at least one mask feature oriented along a first direction of the mask layout. The second mask sub-layout comprises one or more sub-resolution gratings having sub-resolution grating lines, the sub-resolution grating lines extending substantially in a second direction of the mask layout, and running over substantially the full width in the second direction of the mask layout, the one or more sub-resolution gratings being not printable for the high or hyper numerical aperture range.

[0086] In some embodiments, as shown in FIG. **2**, a method is disclosed wherein the method **200** comprises the following steps.

[0087] In a first step, the method **200** comprises repetitively defining a mask layout **210** having the mask layout features as described above but for a plurality of sub-resolution grating pitches and/or sizes of the sub-resolution grating lines of the one or more sub-resolution gratings thus obtaining different mask layouts as function of the sub-resolution grating pitch and/or size of the sub-resolution grating lines.

[0088] In a second step, the method **200** comprises simulating lithographic imaging **220** of the mask pattern for the different mask layouts as function of the size of the sub-resolution grating lines. From such simulations imaging quality parameters can be derived. These can be e.g. best depth of focus through pitch and/or highest contrast through pitch for patterns to be printed, but could also include other imaging quality parameters.

[0089] In a third step, the method **200** comprises selecting the mask layout **230** having the best imaging quality parameters.

[0090] It is to be noted that the steps may be performed at least partly in parallel and that based on a first evaluation, certain mask layouts may not be considered anymore while other mask layouts may be defined and simulated further.

[0091] The method may be implemented as an optimization method for thus obtaining an improved mask layout.

[0092] According to some embodiments, these thus involve defining **210** multiple mask layouts with varying sub-resolution grating pitches and/or sizes of the sub-resolution grating lines, simulating lithographic imaging **220** for the layouts, and selecting **230** the one with the best depth of focus and/or highest contrast through pitch of the patterns to be printed. Aside from these optimizations, the method may also account for different lithographic conditions, such as multiple monopole exposure passes or injected aberrations. Further optimization of the mask design, based on other optimization processes could also be implemented simultaneously or in addition thereto.

[0093] In a third aspect, a corresponding system for performing a method as described in the second aspect is disclosed. This system for determining lithographic processing conditions, includes an input for obtaining characteristics of an illumination source and a lithography pattern, and a processor for defining a mask layout to be used. An output for outputting the defined or selected mask layout also is included. In some embodiments, the processor may be programmed for defining mask layouts with different sub-resolution grating pitches and sizes of sub-resolution grating lines, for simulating lithographic imaging for each layout and for selecting the one offering the best depth of focus through pitch and/or highest contrast through pitch, thus providing a further systematic approach to mask design. Such a system may be implemented as a computer program product and a data carrier storing such a program, respectively. These aspects may be specifically designed for enabling the execution of the methods described in the second aspect of the disclosure, facilitating the design and optimization of mask layouts for EUV lithography processes. An example system is shown in FIG. **3**, illustrating the system **300** with the input **310**, the processor **320** and the output **330**.

[0094] By way of illustration, embodiments not being limited thereto, some examples and considerations will be illustrated, showing standard and/or optional features of various embodiments.

[0095] In a first example, the effects of adding sub-resolution gratings of various widths to mask features on a mask are shown in FIG. **4**. The results are shown from the perspective of best focus as well as from the perspective of NILS. FIG. **4** shows (from left to right-upper row) the best focus shift through pitch for mask features for a low-n mask, the 3sigma of the best focus variation and the 1st-0th order phase offset. The pitch of the sub-resolution grating used thereby is SRGpitch=9 nm at wafer scale. In the left drawing of the upper row, the width of the sub-resolution grating lines thereby varies from 0 nm (no sub-resolution grating) to 4 nm at wafer scale, the arrow indicating the direction of increase of the width of the SRG lines.

[0096] FIG. **4** also shows (from left to right-bottom row) the Nils through pitch for mask features, the NILS as function of pitch and defocus when no sub-resolution grating is used and the NILS as function of pitch and defocus when a sub-resolution grating with SRGpitch 9 nm and sub-resolution grating line width of 3 nm. In the left drawing of the bottom row, the arrow indicates the direction of increasing SRG width (no SRG lines, SRG width=1 nm to SRG width 4 nm). In the middle and the right drawing of the bottom row, the arrows indicate the direction of increasing NILS.

[0097] From these results, it can be seen that the application of a sub-resolution grating in a mask may result in enhanced lithography processes when using such mask.

[0098] In a second example, the effects of tuning the use of a sub-resolution grating in the mask layout to the imaging conditions of the EUV lithography on the mask rule checks applied are illustrated. In the example shown, the layout includes horizontal sub-resolution grating lines perpendicular to the vertical main features. FIG. **5** at the left shows that the use of sub-resolution assisted features separated from the vertical pattern would result in tight mask rule checks, whereas FIG. **5** at the right illustrates that sub-resolution grating lines cutting through all mask features avoid mask rule check issues. The situation is illustrated for the use of sub-resolution gratings for a dark field mask. FIG. **5** shows a representation of a sub-resolution grating for a dark field mask and a bright field mask. In the case of a bright field mask, the tone of the sub-resolution grating is inverted for improving the imaging performance.

[0099] Aside from the transmittance, drawn in the bottom portion of FIG. **6**, also a representation of the mask features is shown in the upper portion of FIG. **6**. In FIG. **6**, the mask features **122** and the sub-resolution gratings **140** are indicated in the upper portion illustrating the masks drawn by layers. Furthermore, in the lower portion illustrating the masks drawn by transmission, the reflective portion **152** (induced by a multilayer) and the absorbing portion **154** (induced by the absorber) are shown.

[0100] In a further example, the optimization of the size and pitch of the sub-resolution grating lines is illustrated. In the example different sub-resolution sizes at wafer scale are evaluated as function of different sub-resolution grating pitch. In FIG. **7**, the situation is shown wherein no sub-resolution grating is used, and for the use of a sub-resolution grating having a sub-resolution grating line width at wafer scale of 1 nm, 2 nm, 3 nm, and 4 nm. This situation is shown for a sub-resolution grating pitch of 7 nm, 8 nm, and 9 nm at wafer scale. In the drawings, the arrows indicate the direction of increasing NILS. From the drawing, it can be seen that the best performance for both image contrast and best focus through pitch is obtained for a sub-resolution grating pitch of 9 nm at wafer scale and a sub-resolution grating line size of 3 nm at wafer scale.

[0101] In a fourth example, the impact of the use of a sub-resolution grating in the mask layout for a 1D Metal design layout (mask design shown in the upper portion of FIG. **8**) on the resulting image (shown in the bottom portion of FIG. **8** is shown. In the left portion of FIG. **8**, the result is shown for a mask design without sub-resolution grating whereas in the right portion of FIG. **8** the result is shown for a mask design with sub-resolution grating. It can be seen that the sub-resolution grating is not visible in the image, but significantly improves the pattern image. It can also be seen that the background intensity is decreased, thus reducing the propensity for defects in EUV lithography.

What is claimed is:

1. A mask for Extreme Ultraviolet (EUV) lithography processes in a high or hyper numerical aperture range,

wherein the mask comprises a mask pattern according to a mask layout,

wherein the mask layout is a superposition of:

a first mask sub-layout comprising a plurality of mask features to be printed, wherein the plurality of mask features to be printed comprises at least one mask feature oriented along a first direction of the mask layout; and

a second mask sub-layout comprising one or more sub-resolution gratings having sub-resolution grating lines, wherein the sub-resolution grating lines extend substantially in a second direction of the mask layout and run over substantially a full width in the second direction of the mask layout, wherein the one or more sub-resolution gratings are not printable for the high or hyper numerical aperture range, wherein the mask layout is a result of overlaying the first mask sub-layout and the second mask sub-layout, and

wherein a size for the sub-resolution grating lines is selected based on best focus or highest contrast across various pitches for mask features to be printed.

2. The mask according to claim **1**, wherein a combination of the sub-resolution grating pitch and size of the sub-resolution grating lines of the one or more sub-resolution gratings is selected based on best depth of focus through pitch or highest contrast through pitch.

3. The mask according to claim **1**, wherein the second mask sub-layout comprises no sub-resolution grating at a position of gaps between the plurality of mask features in the first sub-layout.

4. The mask according to claim **1**,

wherein the first direction is different from the second direction and the sub-resolution grating lines cross substantially all mask features, or

wherein the first direction is perpendicular to the second direction.

5. The mask according to claim **4**, wherein the mask is one of a dark field mask or a bright field mask.

6. The mask according to claim **1**, wherein the mask is used in a EUV lithography in a high or hyper numerical aperture range along with an anamorphic optics system in which demagnification for an X-direction is smaller than demagnification in the Y direction, and wherein the first direction along which the plurality of mask features are extending corresponds with the Y direction and the second direction corresponds with the X direction.

7. A computer-implemented method for designing a mask layout for Extreme Ultraviolet (EUV) lithography processes in a high or hyper numerical aperture range, the method comprising:

repetitively defining a mask layout for the mask pattern as a superposition of:

a first mask sub-layout comprising a plurality of mask features to be printed, wherein the plurality of mask features to be printed comprises at least one mask feature oriented along a first direction of the mask layout; and

a second mask sub-layout comprising one or more sub-resolution gratings having sub-resolution grating lines, wherein the sub-resolution grating lines extend substantially in a second direction of the mask layout and run over substantially a full width in the second direction of the mask layout, wherein the one or more sub-resolution gratings are not printable for the high or hyper numerical aperture range,

wherein the mask layout is a result of overlaying the first mask sub-layout with the second mask sub-layout, and

wherein repetitively defining the mask layout is performed for a plurality of sub-resolution pitches or sizes of the sub-resolution grating lines of the one or more sub-resolution gratings to obtain different mask layouts;

simulating lithographic imaging of the mask pattern for each of the different mask layouts as a function of the sub-resolution pitch and size of the sub-resolution grating lines to obtain image quality parameters; and

selecting the mask layout based on best focus or highest contrast across various pitches for mask features to be printed.

8. The computer-implemented method according to claim **7**, further comprising simulating lithographic imaging as a function of multiple monopole exposure passes or injected aberrations.

9. The computer-implemented method according to claim **7**, wherein a combination of the sub-resolution grating pitch and size of the sub-resolution grating lines of the one or more sub-resolution gratings is selected based on best depth of focus through pitch or highest contrast through pitch.

10. The computer-implemented method according to claim **7**, wherein the second mask sub-layout comprises no sub-resolution grating at a position of gaps between the plurality of mask features in the first sub-layout.

11. The computer-implemented method according to claim **7**,

wherein the first direction is different from the second direction and the sub-resolution grating lines cross substantially all mask features, or

wherein the first direction is perpendicular to the second direction.

12. The computer-implemented method according to claim **11**, wherein the mask is one of a dark field mask or a bright field mask.

13. The computer-implemented method according to claim **7**, wherein the mask is used in a EUV lithography in a high or hyper numerical aperture range along with an anamorphic optics system in which demagnification for an X-direction is smaller than demagnification in the Y direction, and wherein the first direction along which the plurality of mask features are extending corresponds with the Y direction and the second direction corresponds with the X direction.

14. A system for determining lithographic processing conditions for EUV lithography processes in a high or hyper numerical aperture range, the system comprising

an input for obtaining characteristics of an illumination source and of a lithography pattern to be created,

a processor programmed for:

repetitively defining a mask layout for the mask pattern as a superposition of

a first mask sub-layout comprising a plurality of mask features to be printed, the plurality of mask features to be printed comprising at least one mask feature oriented along a first direction of the mask layout, and

a second mask sub-layout comprising one or more sub-resolution gratings having sub-resolution grating lines, the sub-resolution grating lines extending substantially in a second direction of the mask layout and running over substantially the full width in the second direction of the mask layout, the sub-resolution gratings further not being printable for the high or hyper numerical aperture range,

the mask layout being the result of overlaying the sub-layouts,

wherein the repetitive defining is performed for a plurality of sub-resolution grating pitches and sizes of the sub-resolution grating lines thus obtaining different mask layouts as function of the sub-resolution grating pitch and as function of the size of the sub-resolution grating lines,

simulating lithographic imaging of the mask pattern for each of the different mask layouts as function of the sub-resolution grating pitch and the size of the sub-resolution grating lines thus obtaining image quality parameters, and

selecting a mask layout based on best focus and/or highest contrast for across various pitches for mask features to be printed,

and

an output for outputting the selected mask layout.

15. The system according to claim **14**, wherein a combination of the sub-resolution grating pitch and size of the sub-resolution grating lines of the one or more sub-resolution gratings is selected based on best depth of focus through pitch or highest contrast through pitch.

16. The system according to claim **14**, wherein the second mask sub-layout comprises no sub-resolution grating at a position of gaps between the plurality of mask features in the first sub-layout.

17. The system according to claim **14**,

wherein the first direction is different from the second direction and the sub-resolution grating lines cross substantially all mask features, or

wherein the first direction is perpendicular to the second direction.

18. The system according to claim **17**, wherein the mask is one of a dark field mask or a bright field mask.

19. The system according to claim **14**, wherein the mask is used in a EUV lithography in a high or hyper numerical aperture range along with an anamorphic optics system in which demagnification for an X-direction is smaller than demagnification in the Y direction, and wherein the first direction along which the plurality of mask features are extending corresponds with the Y direction and the second direction corresponds with the X direction.

20. The system according to claim **14**, wherein the high or hyper numerical aperture range comprises a numerical aperture above 0.5.

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