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(54) **X-RAY SOURCE OPTICS FOR SMALL-ANGLE X-RAY SCATTEROMETRY**

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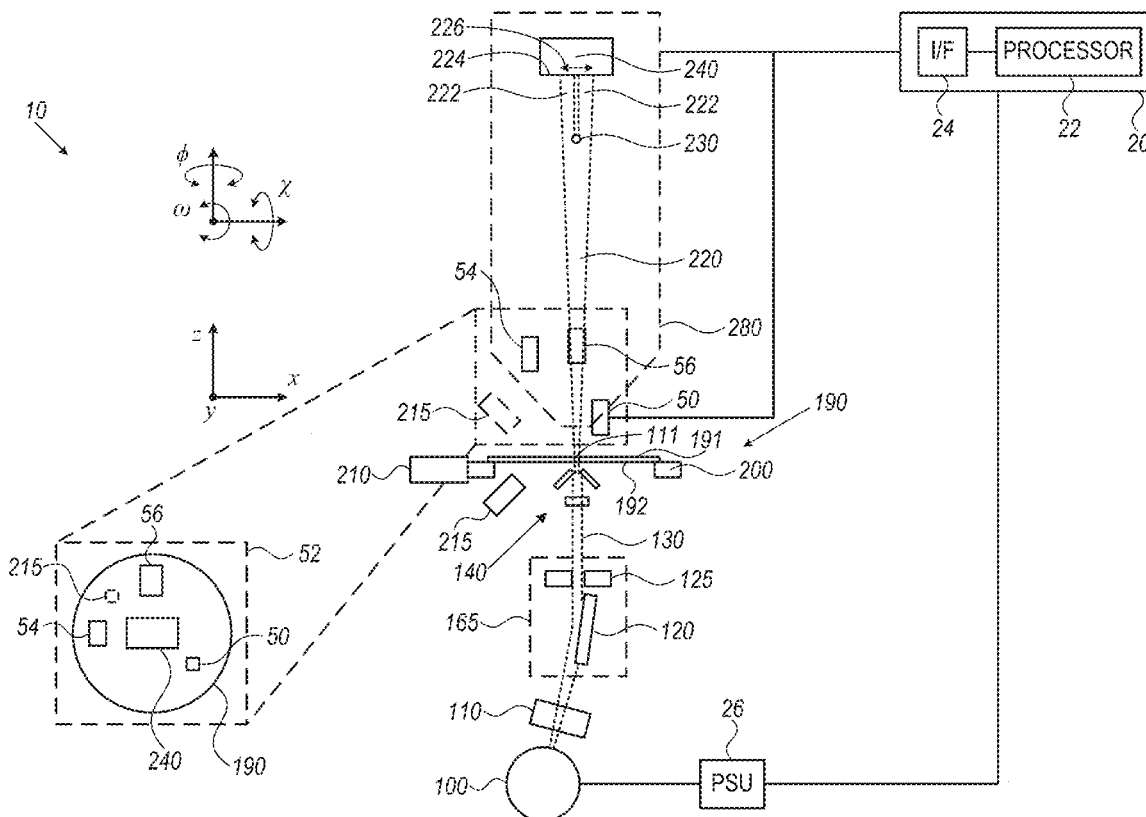
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(57) **ABSTRACT**

An X-ray apparatus includes a mount, an X-ray source, a detector and a beam limiter. The mount is configured to hold a planar sample. The X-ray source is configured to direct a beam of X-rays toward a first side of the sample. The detector is positioned on a second side of the sample, opposite the first side, so as to receive at least a part of the X-rays that have been transmitted through the sample. The beam limiter is positioned on the first side of the sample so as to intercept the beam of the X-rays. The beam limiter includes first and second blades and first and second actuators. The first and second blades have respective first and second edges positioned in mutual proximity so as to define a slit, through which the beam of the X-rays will pass, at a distance smaller than 25 mm from the first side of the sample. The first and second actuators are configured to shift the first and second blades along respective, first and second translation axes so as to adjust a width of the slit.



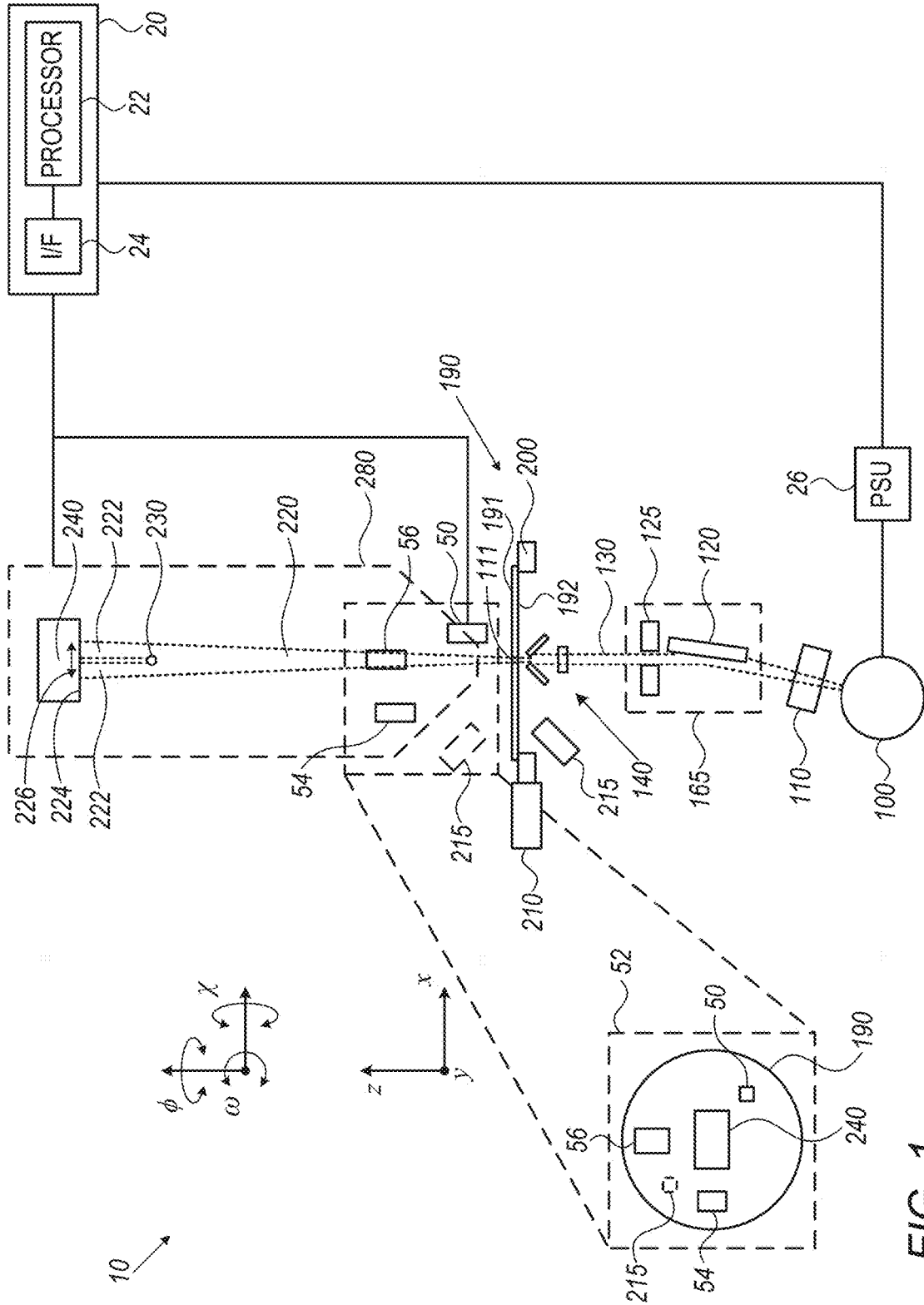


FIG. 1

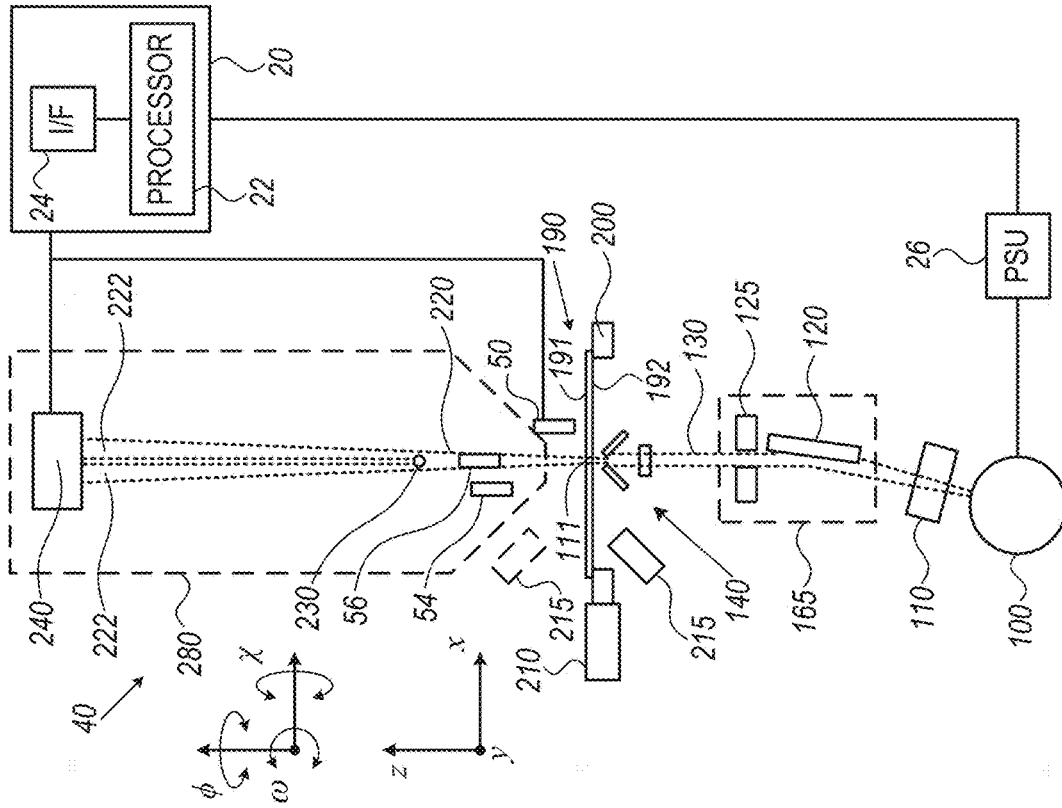


FIG. 3

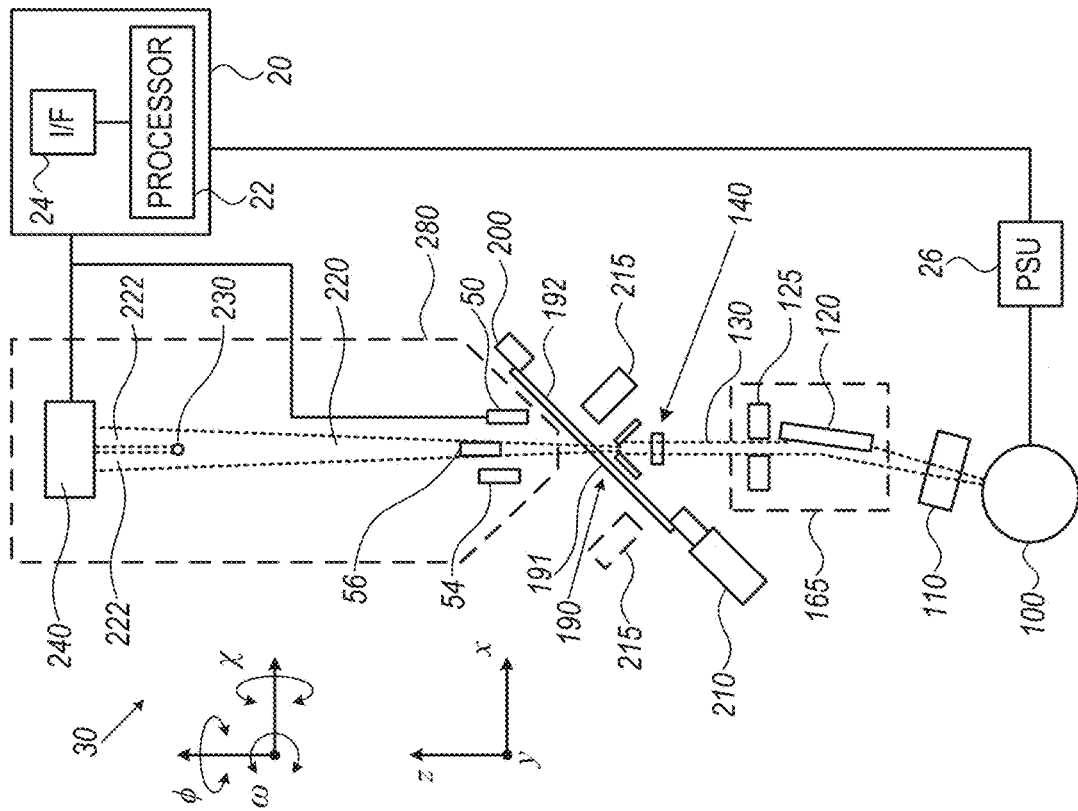


FIG. 2

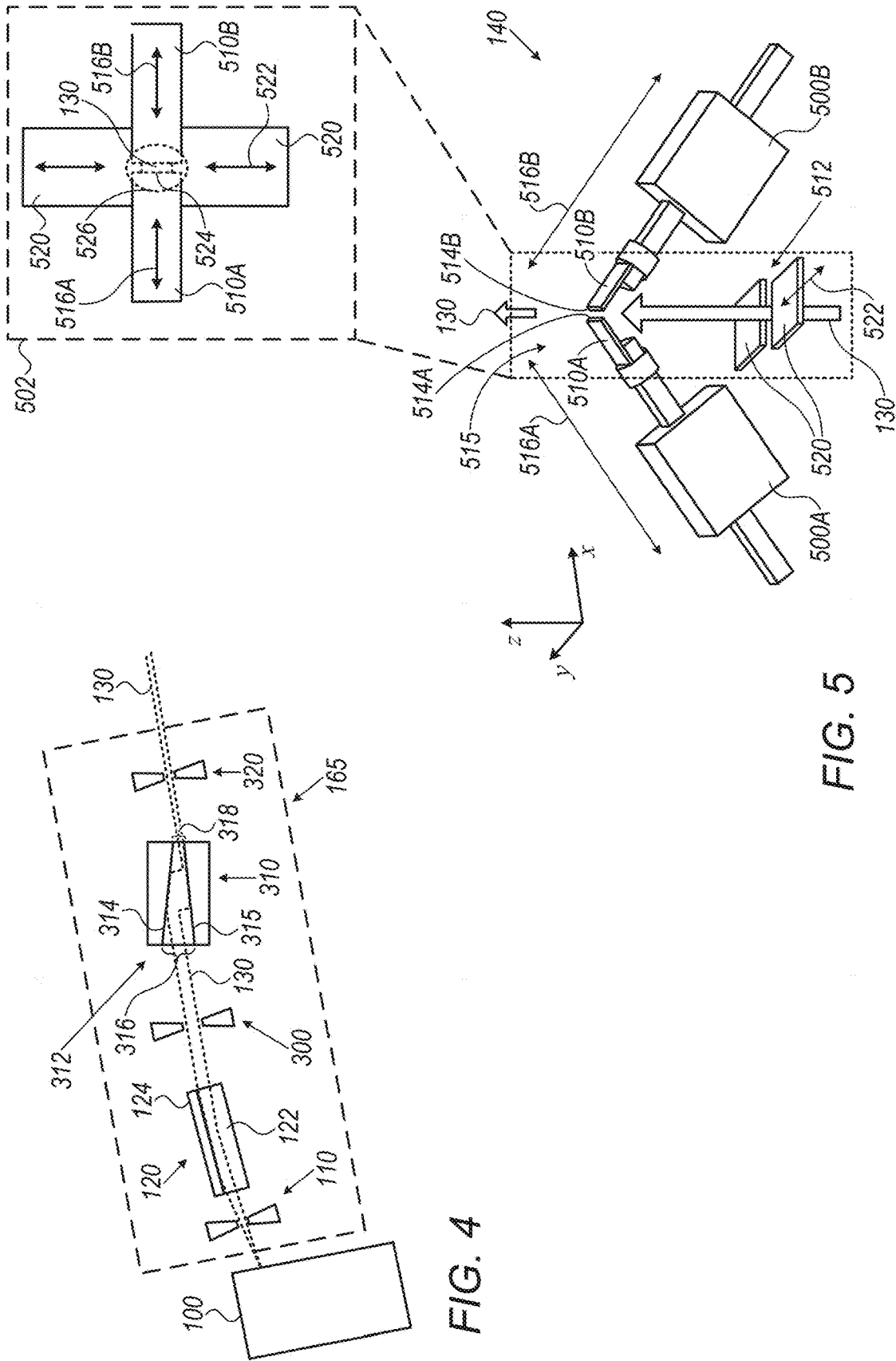


FIG. 4

FIG. 5

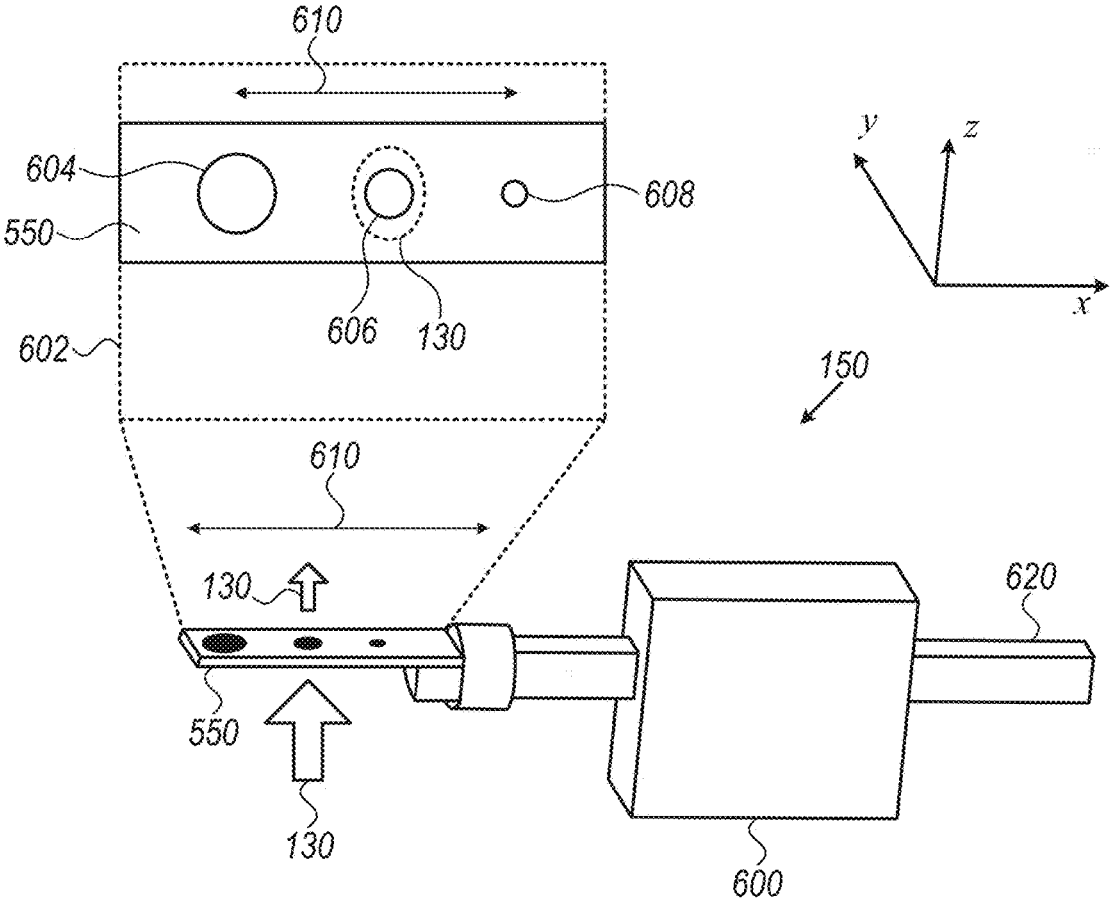
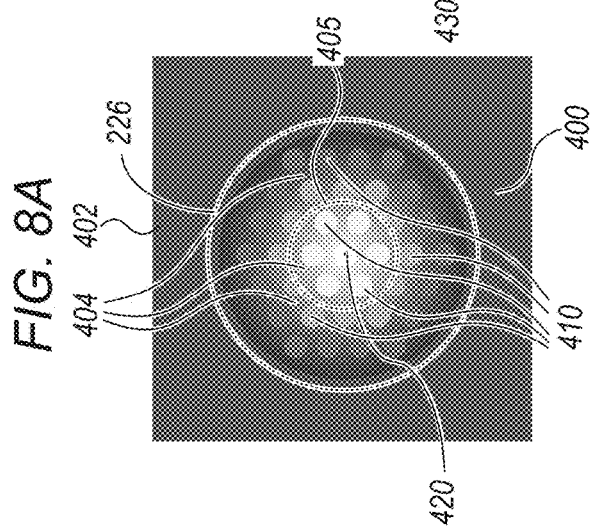
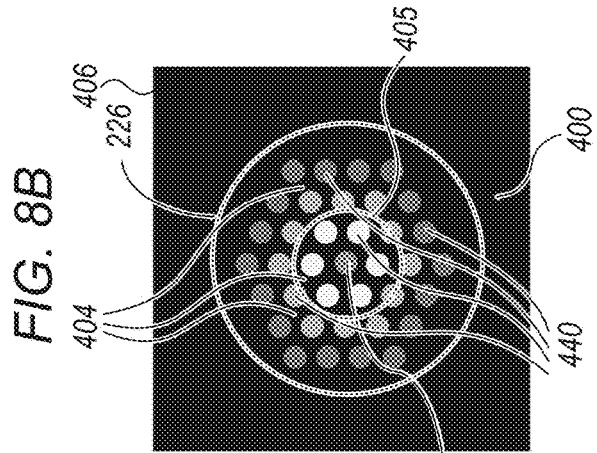
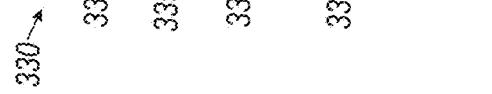
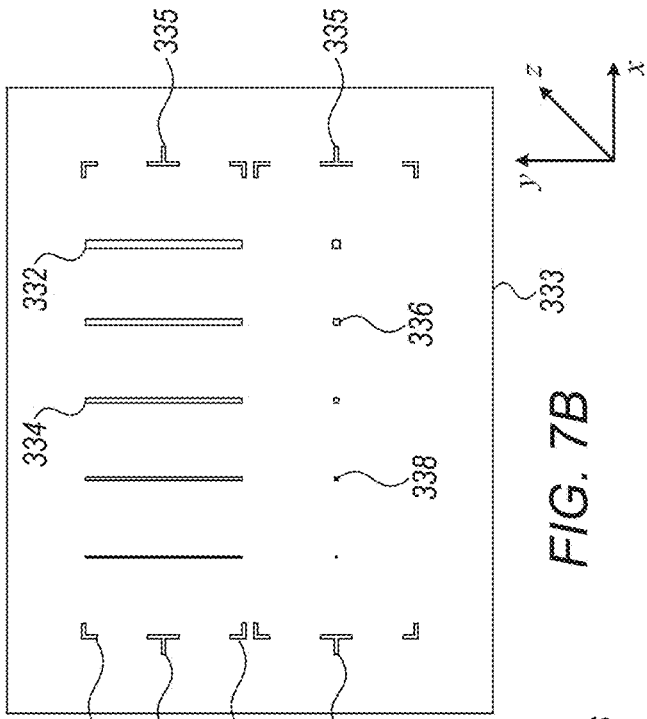


FIG. 6



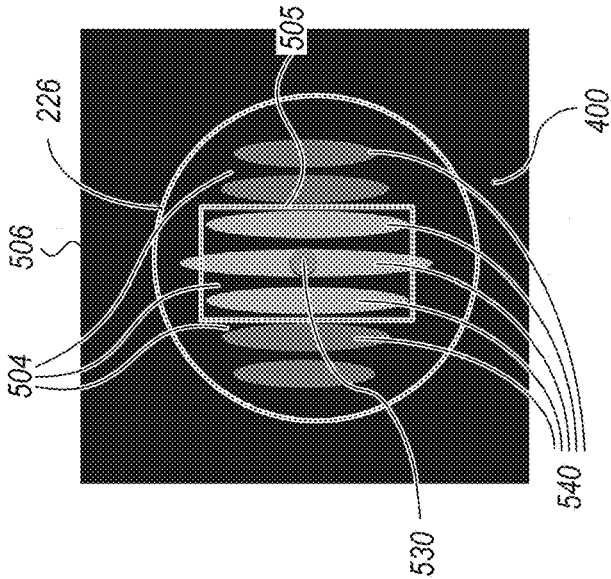


FIG. 9A

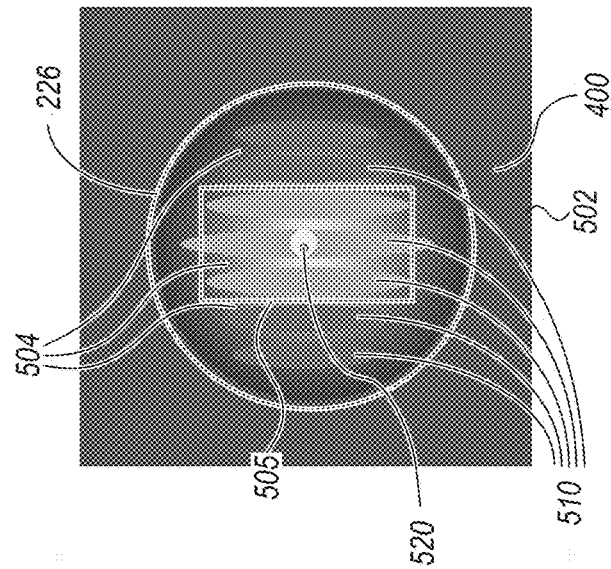


FIG. 9B

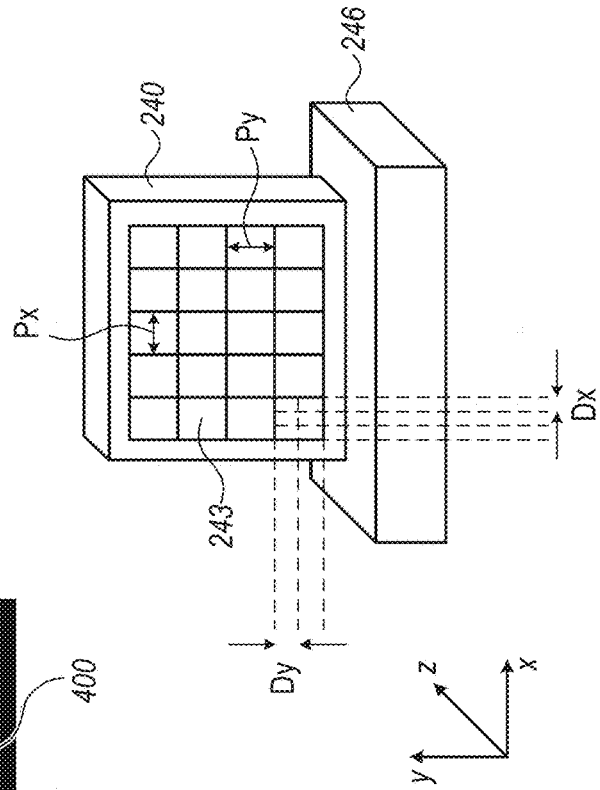


FIG. 10

## X-RAY SOURCE OPTICS FOR SMALL-ANGLE X-RAY SCATTEROMETRY

### CROSS-REFERENCE TO RELATED APPLICATIONS

**[0001]** This application claims the benefit of U.S. Provisional Patent Application 62/661,133, filed Apr. 23, 2018, whose disclosure is incorporated herein by reference.

### FIELD OF THE INVENTION

**[0002]** The present invention relates generally to X-ray analysis, and particularly to methods and systems for measuring geometrical structures of semiconductor devices using X-ray scatterometry.

### BACKGROUND OF THE INVENTION

**[0003]** X-ray scatterometry techniques are used for measuring geometrical structures of semiconductor devices.

**[0004]** For example, U.S. Pat. No. 7,481,579 describes a method for inspection that includes directing a beam of X-rays to impinge upon an area of a sample containing first and second features formed respectively in first and second thin film layers, which are overlaid on a surface of the sample. A pattern of the X-rays diffracted from the first and second features is detected and analyzed in order to assess an alignment of the first and second features.

**[0005]** U.S. Pat. No. 9,606,073 describes apparatus that includes a sample-support that retains a sample in a plane having an axis, the plane defining first and second regions separated by the plane. A source-mount in the first region rotates about the axis, and an X-ray source on the source-mount directs first and second incident beams of X-rays to impinge on the sample at first and second angles along beam axes that are orthogonal to the axis. A detector-mount in the second region moves in a plane orthogonal to the axis and an X-ray detector on the detector-mount receives first and second diffracted beams of X-rays transmitted through the sample in response to the first and second incident beams, and outputs first and second signals, respectively, in response to the received first and second diffracted beams. A processor analyzes the first and the second signals so as to determine a profile of a surface of the sample.

**[0006]** U.S. Pat. No. 6,895,075 describes apparatus for inspection of a sample, the apparatus includes a radiation source and an array of detector elements arranged to receive radiation from a surface of the sample due to irradiation of an area of the surface by the radiation source.

**[0007]** U.S. Pat. No. 7,551,719 describes apparatus for analysis of a sample, the apparatus includes a radiation source, which is adapted to direct a first, converging beam of X-rays toward a surface of the sample and to direct a second, collimated beam of the X-rays toward the surface of the sample. A motion assembly moves the radiation source between a first source position, in which the X-rays are directed toward the surface of the sample at a grazing angle, and a second source position, in which the X-rays are directed toward the surface in a vicinity of a Bragg angle of the sample.

**[0008]** U.S. Pat. No. 8,243,878 describes a method for analysis including directing a converging beam of X-rays toward a surface of a sample having an epitaxial layer formed thereon, and sensing the X-rays that are diffracted from the sample while resolving the sensed X-rays as a

function of angle so as to generate a diffraction spectrum including a diffraction peak and fringes due to the epitaxial layer.

### SUMMARY OF THE INVENTION

**[0009]** An embodiment of the present invention that is described herein provides an X-ray apparatus that includes a mount, an X-ray source, a detector and a beam limiter. The mount is configured to hold a planar sample. The X-ray source is configured to direct a beam of X-rays toward a first side of the sample. The detector is positioned on a second side of the sample, opposite the first side, so as to receive at least a part of the X-rays that have been transmitted through the sample. The beam limiter is positioned on the first side of the sample so as to intercept the beam of the X-rays. The beam limiter includes first and second blades and first and second actuators. The first and second blades have respective first and second edges positioned in mutual proximity so as to define a slit, through which the beam of the X-rays will pass, at a distance smaller than 25 mm from the first side of the sample. The first and second actuators are configured to shift the first and second blades along respective, first and second translation axes so as to adjust a width of the slit.

**[0010]** In some embodiments, the mount is configured to tilt the sample about a tilt axis in a plane of the sample, and the slit is oriented parallel to the tilt axis. In other embodiments, the first and second blades include a material made from a single-crystalline material or a polycrystalline material. In yet other embodiments, the first and second blades are not parallel to one another.

**[0011]** In an embodiment, the first and second translation axes are not parallel to one another. In another embodiment, the beam limiter is configured to control at least one beam parameter, selected from a list consisting of (i) a position of the beam, (ii) a spot size of the beam, (iii) a spot shape of the beam on the first side of the sample, and (iv) a convergence or divergence angle of the beam. In yet another embodiment, the beam limiter is mounted on a stage, which is configured to move the beam limiter relative to at least one of the beam and the sample.

**[0012]** In some embodiments, the stage includes at least a rotation stage. In other embodiments, at least one of the first and second actuators includes one or more piezoelectric linear motors. In yet other embodiments, the apparatus includes first and second movable plates having respective first and second plate edges positioned in mutual proximity so as to define an additional slit, through which the beam of the X-rays will pass, before or after passing through the slit.

**[0013]** In an embodiment, the apparatus includes a third actuator, which is configured to shift at least one of the first and second movable plates along a third translation axis so as to adjust a size of the additional slit. In another embodiment, the apparatus includes a processor, which is configured to shape the beam of the X-rays by aligning a position of the slit and the additional slit relative to one another.

**[0014]** There is additionally provided, in accordance with an embodiment of the present invention, a method including holding a planar sample on a mount. A beam of X-rays is directed from an X-ray source toward a first side of the sample. At least a part of the X-rays that have been transmitted through the sample are received from a detector positioned on a second side of the sample, opposite the first side. A beam limiter is positioned on the first side of the sample so as to intercept the beam of the X-rays. The beam



limiter includes first and second blades, having respective first and second edges positioned in mutual proximity so as to define a slit, through which the beam of the X-rays will pass, at a distance smaller than 25 mm from the first side of the sample, and first and second actuators. A width of the slit is adjusted by shifting the first and second blades along respective first and second translation axes, using the first and second actuators.

**[0015]** There is further provided, in accordance with an embodiment of the present invention, an X-ray optical device that includes a crystal, an X-ray mirror and one or more slits. The crystal contains a channel having an entrance aperture, an exit aperture, and opposing internal faces arranged so that the channel tapers from the entrance aperture to the exit aperture. The X-ray mirror includes a curved substrate with a multilayer coating, which is configured to collect and direct a beam of X-rays emitted from a source into the entrance aperture of the channel with a first beam diameter, so that the beam is emitted from the exit aperture with a second beam diameter, less than the first beam diameter. One or more slits interposed between the X-ray mirror and the crystal, so that the beam passes through the slits before entering the entrance aperture of the channel.

**[0016]** In some embodiments, the X-ray mirror is configured to adjust a divergence and intensity of the beam. In other embodiments, the device includes a blade and an actuator. The blade has an array of apertures of different, respective sizes passing therethrough. The actuator is configured to position the blade in a path of the beam emitted from the exit aperture of the crystal and to translate the blade so as to position different ones of the aperture in the path.

**[0017]** In an embodiment, the crystal includes a single-crystal made from germanium. In another embodiment, the opposing internal faces are not parallel to one another.

**[0018]** There is additionally provided, in accordance with an embodiment of the present invention, an X-ray apparatus that includes a mount, an X-ray source, a detector, an optical gauge and a motor. The mount is configured to hold a planar sample having a first side, which is smooth, and a second side, which is opposite the first side and on which a pattern has been formed. The X-ray source is configured to direct a first beam of X-rays toward the first side of the sample. The detector is positioned on the second side of the sample so as to receive at least a part of the X-rays that have been transmitted through the sample and scattered from the pattern. The optical gauge is configured to direct a second beam of optical radiation toward the first side of the sample, to sense the optical radiation that is reflected from the first side of the sample, and to output a signal, in response to the sensed optical radiation, that is indicative of a position of the sample. The motor is configured to adjust an alignment between the detector and the sample in response to the signal.

**[0019]** In some embodiments, the signal is indicative of at least one position parameter, selected from a group of position parameters consisting of a distance between the sample and the detector and an orientation of the sample relative to the detector. In other embodiments, the orientation of the sample includes an inclination angle of the sample relative to a surface of the detector. In yet other embodiments, the sample includes a single-crystal material, and the X-ray apparatus includes an additional detector, which is configured to measure an intensity of at least a portion of the X-rays that has been diffracted from a lattice

plane of the single-crystal material, and the X-ray apparatus further includes a controller, which is configured to calibrate an orientation of the first beam of X-rays with respect to the lattice plane responsively to the measured intensity.

**[0020]** In an embodiment, the X-ray apparatus includes a processor, which is configured to instruct the optical gauge to direct the second beam toward multiple locations on the first side of the sample so as to output multiple respective signals indicative of multiple respective optical radiations reflected from the multiple locations. The processor is further configured to display, based on the multiple signals, a three-dimensional (3D) map indicative of the position of the sample at least at the multiple locations. In another embodiment, the processor is configured to estimate, based on the multiple locations, one or more additional positions of the sample at additional one or more respective locations on the first side, and to display the additional locations on the 3D map.

**[0021]** In some embodiments, the X-ray apparatus includes an energy dispersive X-ray (EDX) detector assembly, which is configured to measure X-ray fluorescence emitted from the pattern at the position of the sample, and to output an electrical signal indicative of an intensity of the X-ray fluorescence measured at the position. In other embodiments, the EDX detector assembly includes a silicon-based or a germanium-based solid-state EDX detector.

**[0022]** There is additionally provided, in accordance with an embodiment of the present invention, a method including holding, on a mount, a planar sample having a first side, which is smooth, and a second side, which is opposite the first side and on which a pattern has been formed. A first beam of X-rays is directed toward the first side of the sample. At least a part of the X-rays that have been transmitted through the sample and scattered from the pattern is received from a detector positioned on the second side of the sample. A second beam of optical radiation is directed toward the first side of the sample for sensing the optical radiation that is reflected from the first side of the sample, and a signal that is indicative of a position of the sample, is output in response to the sensed optical radiation. An alignment, between the detector and the sample, is adjusted in response to the signal.

**[0023]** There is further provided, in accordance with an embodiment of the present invention, an X-ray apparatus that includes a mount, an X-ray source, a detector, a motor, and a controller. The mount is configured to hold a sample that includes a single-crystal material and has a first side and a second side, which is opposite the first side. The X-ray source is configured to direct a beam of X-rays toward the first side of the sample. The detector is positioned on the second side of the sample and is configured to receive at least a portion of the X-rays that have been diffracted from a lattice plane of the single-crystal material. The motor is configured to adjust an alignment between the detector and the sample. The controller is configured to measure an orientation of the sample relative to the detector based on the diffracted X-rays and to drive the motor to adjust the alignment responsively to the measured orientation.

**[0024]** There is additionally provided, in accordance with an embodiment of the present invention, an X-ray apparatus that includes a mount, an X-ray source, a detector, an actuator, and a controller. The mount is configured to hold a sample. The X-ray source is configured to direct a beam of X-rays toward a first side of the sample. The detector is

positioned on a second side of the sample, opposite the first side, so as to receive at least a portion of the X-rays that have been transmitted through the sample and to output signals indicative of an intensity of the received X-rays. The actuator is configured to scan the detector over a range of positions on the second side of the sample so as to measure the transmitted X-rays as a function of a scattering angle. The controller is coupled to receive the signals output by the detector and to control the actuator, responsively to the signals, so as to increase an acquisition time of the detector at first positions where the intensity of the received X-rays is weak relative to the acquisition time at second positions where the intensity of the received X-rays is strong.

**[0025]** In some embodiments, the detector includes an array of sensor elements having a predefined pitch, and the actuator is configured to step the detector across the range of positions with a resolution that is finer than the predefined pitch. In other embodiments, the array includes a two-dimensional matrix of the sensor elements, and the actuator is configured to step the detector with the resolution that is finer than the pitch along both height and width axes of the matrix.

**[0026]** In an embodiment, the sample includes one or more high aspect ratio (HAR) features having an aspect ratio larger than ten, and the actuator is configured to scan the detector over the range of positions so as to measure the transmitted X-rays scattered from the HAR features. In another embodiment, the controller is configured to control the acquisition time so that the detector receives a predefined intensity range at the first and second positions.

**[0027]** There is also provided, in accordance with an embodiment of the present invention, a method including holding a sample on a mount. A beam of X-rays is directed toward a first side of the sample. At least a portion of the X-rays that have been transmitted through the sample is received from a detector positioned on a second side of the sample, opposite the first side, and signals indicative of an intensity of the received X-rays are output. The detector is scanned, by an actuator, over a range of positions on the second side of the sample so as to measure the transmitted X-rays as a function of a scattering angle. The signals output are received by the detector and the actuator is controlled, responsively to the signals, so as to increase an acquisition time of the detector at first positions where the intensity of the received X-rays is weak relative to the acquisition time at second positions where the intensity of the received X-rays is strong.

**[0028]** There is additionally provided, in accordance with an embodiment of the present invention, an X-ray apparatus that includes a first mount, an X-ray source, a detector, and a beam blocker. The first mount is configured to hold a sample. The X-ray source is configured to direct a beam of X-rays toward the sample. The detector is positioned to receive the X-rays that have been transmitted through the sample, at least part of the transmitted beams are scattered from the sample over a range of angles. The beam blocker includes a second mount made of a material that is transparent to the X-rays and one or more pieces of an X-ray opaque material held within the second mount, and is positionable so that the X-ray opaque material blocks the X-rays in a part of the range of angles, while the X-rays at the angles surrounding the blocked part of the range pass through the mount to the detector.

**[0029]** In some embodiments, at least one of the pieces of the X-ray opaque material is ellipsoidal. In other embodiments, the mount includes a polymer. In yet other embodiments, the mount includes diamond.

**[0030]** In an embodiment, at least part of the blocked X-rays include X-rays transmitted through the sample without being scattered. In another embodiment, the X-ray apparatus includes a processor, which is configured to measure an intensity of the X-rays received by the detector, and to position the beam blocker relative to the transmitted beam responsively to the measured intensity. In yet another embodiment, at least one of the pieces of the X-ray opaque material is held within a recess of the mount.

**[0031]** In some embodiments, the mount includes a sheet made from (i) biaxially-oriented polyethylene terephthalate (BoPET) polyester, or (ii) poly (4,4'-oxydiphenylene-pyromellitimide) polyimide. In other embodiments, at least one of the pieces of the X-ray opaque material includes gold, tantalum, or tungsten. In yet other embodiments, the pieces of the X-ray opaque material include at least a first piece and a second piece, having a different size and laid out in an array at a predefined distance from one another.

**[0032]** The present invention will be more fully understood from the following detailed description of the embodiments thereof, taken together with the drawings in which:

#### BRIEF DESCRIPTION OF THE DRAWINGS

**[0033]** FIGS. 1-3 are schematic illustrations of small-angle X-ray scattering (SAXS) systems, in accordance with embodiments of the present invention;

**[0034]** FIG. 4 is a schematic illustration of a beam conditioning assembly, in accordance with an embodiment of the present invention;

**[0035]** FIGS. 5 and 6 are schematic illustrations of slit assemblies, in accordance with embodiments of the present invention;

**[0036]** FIGS. 7A and 7B are schematic illustrations of beam blocking assemblies, in accordance with embodiments of the present invention;

**[0037]** FIG. 8A is a schematic illustration of an image indicative of the intensity of an X-ray beam sensed by a detector without a beam blocker, in accordance with another embodiment of the present invention;

**[0038]** FIG. 8B is a schematic illustration of an image indicative of the intensity of an X-ray beam sensed by a detector in the presence of a beam blocker, in accordance with an embodiment of the present invention;

**[0039]** FIG. 9A is a schematic illustration of an image indicative of the intensity of a scattered X-ray beam sensed by a detector without a beam blocker, in accordance with another embodiment of the present invention;

**[0040]** FIG. 9B is a schematic illustration of an image indicative of the intensity of a scattered X-ray beam sensed by a detector in the presence of beam blocker, in accordance with an embodiment of the present invention; and

**[0041]** FIG. 10 is a schematic illustration of a scanning scheme in which an X-ray detector comprising an array of sensors is moved at steps smaller than the inter-distance of the sensors, for improved angular resolution, in accordance with an embodiment of the present invention.

## DETAILED DESCRIPTION OF EMBODIMENTS

## Overview

**[0042]** Embodiments of the present invention that are described hereinbelow provide improved methods and systems for analyzing geometrical features formed in various types of semiconductor devices and test structures. X-ray scatterometry techniques for analyzing features, such as small-angle X-ray scattering (SAXS) methods, typically apply X-rays whose wavelengths are on the order of one angstrom. Such wavelengths are suitable for measuring High Aspect Ratio (HAR) features such as HAR holes or trenches fabricated in semiconductor wafers. Measuring geometrical and other properties of the features is carried out based on analyzing the intensities of the X-rays scattered from the wafer at various angles.

**[0043]** In some embodiments, a SAXS system comprises a motorized stage, which is configured to move a planar sample, such as a wafer having front and back surfaces facing one another, wherein the front surface comprises various types of features, such as HAR features. Additionally or alternatively, the back surface of the wafer may be patterned with similar and/or other types of features.

**[0044]** In some embodiments, the SAXS system comprises an X-ray source, which is configured to direct a beam of X-rays toward the back surface of the wafer. The SAXS system further comprises at least one detector, facing the front surface of the wafer, the detector is configured to sense at least part of the X-rays that have been scattered from and/or transmitted through the wafer. The detector is configured to produce electrical signals indicative of the intensity of the X-rays scattered from HAR features in the front surface of the wafer, and received by the detector.

**[0045]** In some embodiments, the SAXS system comprises a processor, which is configured to measure properties of the HAR features in question, based on the electrical signals received from the detector.

**[0046]** In some embodiments, the SAXS system comprises a beam conditioning assembly, positioned between the X-ray source and the back surface of the wafer, and configured to adjust properties of the X-ray beam. The beam conditioning assembly comprises a crystal containing a v-shaped channel having an entrance aperture, an exit aperture, and opposing internal faces arranged so that the channel tapers from the entrance aperture to the exit aperture. The beam conditioning assembly further comprises an X-ray mirror, having a curved substrate with a multilayer coating. The mirror is configured to collect the beam and direct the collected beam into the entrance aperture of the channel with a first beam diameter, so that the beam that is emitted from the exit aperture has a second beam diameter, smaller than the first beam diameter.

**[0047]** In some embodiments, the SAXS system comprises a first slit, which is positioned between the X-ray source and the back surface of the wafer so as to intercept the beam and to adjust spatial properties of the intercepted beam. The first slit comprises first and second movable blades that are typically not parallel to one another. The edges of the first and second blades are positioned in close proximity to one another so as to define the slit. In some embodiments, the processor is configured to move the edges of the first and second blades so as to control spatial properties of the beam by adjusting the width of the slit.

**[0048]** In alternative embodiments, the SAXS system comprises a second slit, positioned between the X-ray source and the back surface of the wafer. The second slit comprises a movable blade having multiple scatterless-pinholes, each of which having a different width. The processor is configured to position a selected scatterless-pinhole to intercept the beam by moving the movable blade, so as to control the spatial properties of the beam.

**[0049]** In some embodiments, the SAXS system comprises an optical gauge, which is configured to direct a light beam toward the back side of the wafer, to sense the optical radiation reflected therefrom using a detector, and, in response to the sensed optical radiation, to output, by the detector, a signal that is indicative of the position of the wafer. Based on the signal, the processor is configured to estimate position parameters, such as the distance between the wafer and the detector, and the orientation of the wafer relative to the detector. The SAXS system further comprises a motor, which is controlled by the processor so as to align the orientation between the X-ray beam and the wafer in response to the signal.

**[0050]** In some embodiments, the wafer comprises single-crystalline material, and the detector is configured to measure one or more beams diffracted from a lattice plane of the single crystal. The SAXS system further comprises a controller, which is configured to calibrate the position of the optical gauge relative to the lattice plane in response to the measured diffraction. Based on the diffracted X-rays, the controller is further configured to measure the orientation of the wafer relative to the detector, and to drive at least one motor to align the orientation between the wafer and the incident X-ray beam, based on the measured orientation. In other embodiments, the processor may carry out at least some of the operations described above, instead of the controller.

**[0051]** In some embodiments, the SAXS system comprises a detector mounted on one or more actuators, which are configured to move the detector with respect to the scattered X-rays, over a range of positions on the front surface of the wafer, so as to measure the intensities of the transmitted X-rays as a function of scattering angle. This configuration allows to measure the intensities of the transmitted X-rays with increased angular resolution than is possible by the native resolution of the detector elements. In some embodiments, the processor is configured to control the actuator, in response to electrical signals produced by the detector, so that the acquisition time of the detector inversely depends on the intensity of the sensed X-rays.

**[0052]** In some embodiments, the detector comprises a two-dimensional array (also referred to as a matrix) of sensor elements having a predefined pitch along height and width axes of the matrix. The actuator is configured to step the detector across the range of positions at a finer resolution than the predefined pitch along both height and width axes.

**[0053]** In some embodiments, the SAXS system comprises a beam blocker having one or more beam stoppers. The beam blocker comprises a mount made of a material that is transparent to the X-rays. The one or more beam stoppers are held within the mount, and are made from a material at least partially opaque to the X-ray beam. The beam blocker may be positioned so that the one or more beam stoppers block the X-rays in a part of the range of angles, whereas the X-rays at the angles surrounding the blocked part of the beam, pass through the mount to the detector. In an embodi-

ment, at least one of the beam stoppers has an ellipsoidal shape with smooth edge so as to prevent scattering of the beam from the beam stopper.

**[0054]** The disclosed techniques improve the sensitivity of SAXS systems to detect small geometrical changes in HAR features, by improving the angular resolution at which the X-ray beams scattered from HAR features are sensed by the detector. Moreover, the disclosed techniques may be used for reducing the footprint of SAXS systems while maintaining measurements in high sensitivity and resolution.

#### System Description

**[0055]** FIG. 1 is a schematic illustration of a small-angle X-ray scattering (SAXS) system **10**, in accordance with an embodiment of the present invention. In some embodiments, SAXS system **10**, also refers to herein as “system **10**” for brevity, is configured to measure features on a sample, in the present example, a wafer **190**, using scatterometry techniques, as will be described hereinbelow.

**[0056]** In some embodiments, wafer **190** may comprise any suitable microstructure or materials, such as a single-crystal, a poly-crystal, an amorphous microstructure or any suitable combination thereof, such as different microstructures or materials at different locations of wafer **190**.

**[0057]** In some embodiments, system **10** comprises an X-ray excitation source, referred to herein as a source **100**, driven by a high-voltage power supply unit (PSU) **26**. In some embodiments, source **100** is configured to emit an X-ray beam **130**, also referred to herein as “incident beam **130**” or “beam **130**” for brevity, having a suitable energy to pass through wafer **190**.

**[0058]** In some embodiments, source **100** is configured to generate an intense X-ray emission having a wavelength equal to or smaller than 0.1 nm with an effective spot-size of about 150  $\mu\text{m}$  or less.

**[0059]** In some embodiments, source **100** may comprise any suitable type of high-brightness X-ray source, such as, but not limited to (a) a fixed solid anode, (b) a rotating solid anode, (c) a liquid metal, or (d) a synchrotron. In some embodiments, the fixed solid anode-based source comprises a micro-focus X-ray tube in which high-energy electrons ( $\geq 50$  keV) in a vacuum are incident with a molybdenum (Mo) or silver (Ag) anode or any other suitable metallic element or alloy. Such micro-focus X-ray tubes are provided by multiple suppliers such as, but not limited to, Incoatec GmbH (Hamburg, Germany), or rtw RONTGEN-TECHNIK DR. WARRIKHOFF GmbH & Co. (Berlin, Germany).

**[0060]** In some embodiments, the rotating solid anode micro-focus X-ray source may comprise a Mo or Ag anode or any other suitable metallic element or alloy. Suitable rotating anode X-ray sources are provided by multiple suppliers, such as, Bruker AXS GmbH (Karlsruhe, Germany).

**[0061]** In some embodiments, the liquid metal X-ray source comprises an anode in a molten state. The anode may comprise any suitable one or more elements or alloys, such as alloys of gallium (Ga) and indium (In). A suitable liquid metal X-ray source may be selected, for example, from one or more of the MetalJet products offered by eXcillum AB (Kista, Sweden).

**[0062]** In some embodiments, a synchrotron-based source that comprise a compact electron accelerator-based X-ray

source, such as the those provided by Lyncean Technologies (Fremont, Calif. 94539, USA) and others being developed by the scientific community.

**[0063]** In some embodiments, wafer **190** may comprise a semiconductor wafer having surfaces **191** and **192**. In some embodiments, surface **191** comprises high aspect ratio (HAR) features produced, on surface **191** and/or into the bulk of wafer **190** or materials deposited thereon, using any suitable semiconductor processes, such as deposition, lithography and etching. Note that in these embodiments, surface **192** typically remains flat and smooth and does not comprise HAR structures or another pattern produced by lithography and etching. It will be understood that during the production of features on surface **191**, some layers may be deposited as a blanket on some locations of surface **192**, e.g., using chemical vapor deposition (CVD) processes, and may cause some unintended topography on surface **192**.

**[0064]** In other embodiments, at least part of surface **192** may be patterned with the aforementioned HAR features and/or with any other suitable types of features. In alternative embodiments, only surface **192** may comprise the aforementioned HAR features.

**[0065]** In the context of the present disclosure, and in the claims, the term “aspect ratio” refers to an arithmetic ratio between the depth and width (e.g., diameter in the case of a circular hole), or between the height and width of a given feature formed in wafer **190**. Furthermore, the term “high aspect ratio (HAR)” typically refers to an aspect ratio higher than 10. The HAR structures, also referred to herein as HAR features, may comprise various types of three-dimensional (3D) structures formed, for example, on a logic device (e.g., a microprocessor), or a NAND flash memory device, or a dynamic random-access memory (DRAM) device, or on any other device.

**[0066]** In some embodiments, the HAR features may comprise one or more Fin field-effect transistors (FETs), gate-all-around (GAA) FETs, nanowire FETs of a complementary metal-oxide semiconductor (CMOS) device, an access transistor of a DRAM device, one or more channels of a 3D NAND flash device, one or more 3D capacitors of a DRAM device, or any other type of HAR feature.

**[0067]** In some embodiments, system **10** comprises a computer **20**, which comprises a processor **22**, an interface **24** and a display (not shown). Processor **22** is configured to control various components and assemblies of system **10** described below, and to process electrical signals received from a movable detector assembly, referred to herein as a detector **240**. Interface **24** is configured to exchange electrical signals between processor **22** and the respective components and assemblies of system **10**.

**[0068]** Typically, processor **22** comprises a general-purpose processor with suitable front end and interface circuits, which is programmed in software to carry out the functions described herein. The software may be downloaded to the processor in electronic form, over a network, for example, or it may, alternatively or additionally, be provided and/or stored on non-transitory tangible media, such as magnetic, optical, or electronic memory.

**[0069]** In some embodiments, beam **130** is emitted from source **100** and passes through a shutter and slit assembly of system **10**, referred to herein as “assembly **110**,” made from any suitable material opaque to X-rays. In some embodiments, processor **22** is configured to set the position of

assembly 110 using one or more controlled actuators, such as motors or piezoelectric-based drives (not shown).

[0070] In some embodiments, assembly 110 is configured to improve the user safety of system 10 by blocking any X-ray radiation deflected from the designed optical path of beam 130. In some embodiments, processor 22 is configured to adjust the position and size of the slits, so as to control the divergence and spatial shape of beam 130.

[0071] In some embodiments, system 10 comprises additional slits, controlled by processor 22 for adjusting the divergence, intensity and spot-size of beam 130, and for blocking undesired scattered radiation.

[0072] In some embodiments, system 10 comprises a beam conditioning assembly, referred to herein as “assembly 165,” whose structure is described in detail in FIG. 4 below. In some embodiments, assembly 165 comprises optical elements, such as a mirror 120 and slits 125. Mirror 120 is configured to collect beam 130 from source 100 and assembly 110 and shape the optical properties of beam 130. For example, mirror 120 is configured to produce a collimated beam or a focused beam, or a combination thereof (e.g., collimated in x-direction and focused in y-direction). Slits 125 are configured to adjust the properties of beam 130, such as the divergence angle and the spot-size of the beam exiting mirror 120.

[0073] In some embodiments, beam conditioning assembly 165 may comprise a vacuum chamber so as to prevent degradation of one or more of the aforementioned optical elements caused by the interaction between air and ionizing radiation on the surface of the optical elements.

[0074] In some embodiments, beam conditioning assembly 165 may have multiple configurations, some of which are described in detail in FIG. 4 below. For example, processor 22 may instruct beam conditioning assembly 165 to shape a first beam 130 as a collimated beam having a small spatial extent (i.e., spot size). Processor 22 may use this beam configuration for measuring features disposed on a small sized test pad, as is the case of logic applications in which metrology is performed on test structures laid out in the scribe line between adjacent dies of wafer 190.

[0075] In another example, wafer 190 may comprise a memory device (e.g., DRAM, NAND flash) having large arrays of repeating features (e.g., in the memory blocks), or a logic device having memory sections. In some embodiments, processor 22 may apply to a selected memory block of the die, a second beam 130 having a larger spot size and higher intensity compared to first beam 130. Processor 22 may exchange the mirror 122 to focus beam 130 on the active surface of detector 240 so as to increase the resolution of the respective SAXS system (e.g., system 10, 30, or 40 described above).

[0076] In some embodiments, system 10 comprises a beam limiter, also referred to herein as a slit assembly 140, which comprises one or more slits and/or movable blades described in detail in FIGS. 5 and 6 below. Slit assembly 140 is configured to control and/or refine the position and/or spot size and/or shape and/or convergence or divergence angle of incident beam 130 on surface 192 of wafer 190.

[0077] In some embodiments, system 10 comprises a motorized rotation stage (not shown) having a rotation axis about the y-axis and centered at surface 191. In some embodiments, source 100, beam conditioning assembly 165, and one or more of slit assemblies 110 and 140 are mounted

on the rotation stage, which is controlled by a motion controller and/or by processor 22.

[0078] In some embodiments, processor 22 may adjust or calibrate the angle between incident beam 130 and a normal to surface 192 of wafer 190, so as to improve the measurement conditions of system 10.

[0079] In some embodiments, system 10 comprises a chuck 200 having wafer 190 mounted thereon. Chuck 200 is configured to mechanically support wafer 190 and to allow directing beam 130 to most of the area (e.g., excluding, at least some part of, the bevel of wafer 190 as shown in FIG. 1), or over the entire area of surface 192.

[0080] In some embodiments, chuck 200 may comprise a ring-shaped wafer support, but additionally or alternatively, chuck 200 may comprise any other suitable design, such as a three-point kinematic mount.

[0081] In some embodiments, system 10 comprises a mount, for example, a motorized  $\chi\zeta\omega\phi$ -stage, referred to herein as “a stage 210,” having chuck 200 mounted thereon. Stage 210 is controlled by processor 22 in a xyz coordinate system of system 10, and is designed as an open frame (i.e., having no material in the center) so as to allow incident beam 130 to directly impinge on surface 192 of wafer 190.

[0082] In some embodiments, stage 210 is configured to move wafer 190 relative to beam 130 in x and y directions, so as to set a desired spatial position of wafer 190 relative to incident beam 130. Stage 210 is further configured to move wafer 190 along z-axis so as to improve the focus of beam 130 at the desired position on surface 192, or at any other suitable position on wafer 190. Stage 210 is further configured to apply rotations  $\chi$  and/or  $\omega$  about respective x-axis and y-axis parallel to surface 192 of wafer 190, and to apply azimuthal rotation  $\phi$  about z-axis perpendicular to surface 192 of wafer 190.

[0083] In some embodiments, processor 22 is configured to select a predefined azimuth  $\phi$  so to align beam 130 with selected features in the structures to be measured. For example, processor 22 may select a first azimuth  $\phi_1$  (not shown) so to align beam 130 relative to line structures arranged in a one-dimensional (1D) on wafer 190. Moreover, processor 22 may select a second azimuth  $\phi_2$  (not shown) so to align beam 130 relative to a pattern or arrays of holes or vias arranged in a two-dimensional (2D) pattern, such as rectangular or hexagonal lattice, on wafer 190.

[0084] In alternative embodiments, wafer 190 is mounted on a suitable stationary fixture (instead of stage 210), such that processor 22 can move source 100, and the aforementioned assemblies (e.g., slit assembly 110, and assemblies 165 and 140), so that the X-ray beam is directed to any one or more desired positions of wafer 190. In other embodiments, system 10 may comprise any other suitable set of mounts, such as a set of stages (e.g., a  $\chi\omega\phi$ -stage for wafer 190, and a xyz-stage for the assemblies described above) and processor 22 is configured to move surfaces 191 and 192 relative to beam 130 by controlling the set of stages.

[0085] In some embodiments, incident beam 130 impinges on surface 192, passes through wafer 190 and is scattered from the aforementioned HAR features formed in surface 191 of wafer 190. In an alternative configuration of wafer 190, surface 192 may comprise HAR features, in addition to or instead of the HAR features patterned in surface 191, as described above. In this wafer configuration, incident beam 130 may also be scattered from the HAR features patterned on surface 192. In some embodiments, detector 240 of

system 10 is configured to detect X-ray photons scattered from the HAR features of both surfaces 191 and 192, as will be described in detail below.

[0086] In some embodiments, incident beam 130 may impinge, at a point 111, perpendicular to surface 192 of wafer 190, or at any other suitable angle relative to wafer 190. In an embodiment, some of incident beam 130 is absorbed as it traverses wafer 190 and a transmitted beam 220 exits surface 191 of wafer 190 in the same direction of incident beam 130. Additional beams 222, scattered from the aforementioned one or more HAR features, exit at different angles to transmitted beam 130 relative to surface 191 of wafer 22.

[0087] In some embodiments, detector 240 is configured to detect X-ray photons of beams 222 impinging, at one or more regions 226, on a surface 224 of detector 240. Detector 240 may comprise any suitable type of one or more detectors such as, but are not limited to, charge-coupled devices (CCDs), CMOS cameras provided by a number of suppliers, or array detectors made from a silicon (Si) or a cadmium telluride (CdTe) detection layer manufactured by DECTRIS Ltd. (Baden, Switzerland) supplying the 1D Mythen detectors and the 2D Pilatus and Eiger series of detectors.

[0088] In some embodiments, detector 240 may be mounted on a high-precision motorized translation and/or rotation stage (not shown), which is configured to move and/or rotate detector 240 based on predefined motion profiles so as to improve the sensing efficiency thereof. Example implementations of the stage and motion control of detector 240 are described in detail in FIG. 10 below.

[0089] In some embodiments, the detectors described above are configured to detect X-rays beams scattered from wafer 190, referred to herein as beams 222, and comprise sensitive elements of sufficiently small size so as to provide the necessary angular resolution for measuring the small-angle scattering intensity distribution from the HAR features of wafer 190.

[0090] In some embodiments, system 10 comprises one or more calibration gauges 215, used in calibrating and setting-up system 10, so as to accurately measure properties of the aforementioned features patterned in wafer 190. At least one of calibration gauges 215 is configured to produce electrical signals indicative of the height and inclination of a given position at wafer 190 relative to a predefined reference, as will be described in detail below. The electrical signals are sent, via interface 24, to processor 22 for analysis.

[0091] In some embodiments, system 10 may comprise two calibration gauges 215. A first calibration gauge 215, facing surface 192 that is typically flat and has no HAR features or other types of pattern, and a second calibration gauge 215, facing surface 191 that is typically patterned and may also have the HAR features described above. In the example configuration of FIG. 1, the second calibration gauge is optional and therefore is shown as a dashed rectangle.

[0092] In other embodiments, system 10 may comprise any other suitable configuration of calibration gauges 215, for example, only the second calibration gauge facing surface 191, or having the aforementioned first and second calibration gauges 215 facing surfaces 192 and 191, respectively.

[0093] In some cases, calibration gauge 215 may respond differently to the height and inclination of a patterned surface (e.g., on surface 191) and a flat surface (e.g.,

non-patterned or blanket surface 192) of wafer 190, and therefore, may require a calibration step before so as to improve the accuracy of the height and inclination measurements.

[0094] In some embodiments, processor 22 may receive from the aforementioned second calibration gauge 215, signals indicative of the height and inclination of surface 191, which is patterned. The pattern may affect (e.g., induce shift in) the measurements carried out by the second calibration gauge. In these embodiments, processor 22 is configured to adjust or calibrate the angle between incident beam 130 and a normal to surface 192 of wafer 190, so as to compensate for the pattern induced shift, and therefore, to improve the quality of measurements carried out by system 10.

[0095] Note that when calibration gauge 215 measures the height and inclination of surface 192, or of any other non-patterned surface, there is typically no shift in the measurements.

[0096] In some embodiments, calibration gauge 215, also referred to herein as an optical gauge, may comprise a light source and a sensor (not shown), or any other suitable configuration. Calibration gauge 215 is configured to measure, at selected coordinates of the x and y axes, the local height (e.g., distance along z-axis) and inclination of surface 192 (e.g., relative to an x-y plane of the xyz coordinate system). In these embodiments, the light source and the sensor are configured to operate in any suitable wavelength, e.g., visible, infrared (IR), or ultraviolet (UV), but typically not in the X-ray range.

[0097] In some embodiments, based on the electrical signals received from calibration gauges 215, processor 22 is configured to calculate and display on the display of system 10, a 3D map indicative of the height and inclination of surfaces 191 and 192, or any other selected plane of wafer 10, relative to any suitable reference, such as the x-y plane of the xyz coordinate system. Processor 22 may calculate the 3D map based on locations measured on surface 192, and additional locations calculated between the measured locations, for example, by interpolating the height and inclination between two or more of the measured locations.

[0098] In some embodiments, processor 22 is further configured to determine the one or more starting positions for any X-ray-based alignment procedures. The alignments procedures are used to determine zero angles, referred to herein as  $\omega_0$  and  $\chi_0$ , of beam 130 relative to one or more scattering structures in question by system 10.

[0099] In some embodiments, by independently measuring the orientation of (a) surfaces 191 and 192, and (b) scattering features in question (e.g., HAR structures) of wafer 190, relative to incident beam 130, processor 22 is configured to calculate the orientation of the scattering features relative to surface 191 of wafer 190. This calculated orientation is particularly important for measuring HAR structure, such as channel holes of 3D NAND flash memory.

[0100] In some embodiments, wafer 190 is typically grown on a crystal having regular arrangement of the atoms comprising the crystal. Subsequently, wafer 190 is sliced from the crystal, such that the surface is aligned in one of several relative directions, referred to herein as the wafer orientation. This is also referred to as the growth plane of the crystalline silicon. The orientation is important for the electrical properties of wafer 190. The different planes have different arrangements of atoms and lattices, which affects

the way the electrical current flows in circuit produced in the wafer. The orientations of silicon wafers are typically classified using Miller indices, such as (100), (111), (001) and (110).

[0101] In some embodiments, system 10 may comprise an integrated optical microscope 50, which may be used for navigation and pattern recognition, and in various other applications, such as optical inspection and/or metrology, and/or for reviewing pattern and other features on wafer 190.

[0102] In some embodiments, optical microscope 50 is electrically coupled to computer 20 and is configured to produce signals indicative of the pattern in question, so that processor 22 could perform the pattern recognition or any other of the aforementioned applications.

[0103] Additionally or alternatively, system 10 may comprise other suitable types of integrated sensors (not shown) configured to provide system 10 with complementary metrology or inspection capabilities.

[0104] In some embodiments, system 10 comprises one or more X-ray diffraction (XRD) detectors, such as XRD detectors 54 and 56, which are configured to detect X-ray photons diffracted from planes substantially perpendicular to surfaces 191 and 192 of wafer 190.

[0105] Reference is now made to an inset 52, which is a top view of system 10. In some embodiments, XRD detectors 54 and 56 are arranged so as to produce diffraction signal that may be used, as will be described below, for wafer alignment based on X-ray photons diffracted from some planes of the crystal lattice. Signals received from at least one of XRD detectors 54 and 56 may also be used for other application.

[0106] The configuration of XRD detectors 54 and 56, optical microscope 50 and calibration gauge 215 (optional) as shown in inset 52, is simplified for the sake of conceptual clarity and is provided by way of example. In other embodiments, system 10 may comprise any other suitable configuration and arrangement of sensors, detectors, microscopes and other suitable components and subsystems.

[0107] Reference is now made back to the side view of FIG. 1. In some embodiments, processor 22 may receive from XRD detectors 54 and 56 signals indicative of intensity of Laue diffraction from planes substantially perpendicular to surfaces 191 and 192 of wafer 190. For example, crystallographic plane (555) is perpendicular to the surface of a silicon wafer having a Miller index (001), referred to herein as Si (001). Additionally or alternatively, processor 22 may receive from at least one of detectors 54, 56 and 240 signals indicative of the intensity of a first portion of beam 222 diffracted from any other lattice plane of wafer 240. These signals are also referred to herein as diffraction signals.

[0108] In some embodiments, processor 22 is configured to use X-rays diffracted from crystal planes substantially normal to surface 191 and sensed by XRD detectors 54 and 56, so as to determine the orientation of the incident beam and/or the direct beam, relative to the lattice planes of a single-crystal wafer.

[0109] In other embodiments, detector 240 is further configured to sense the X-ray photons diffracted from the aforementioned Laue diffraction, and to produce signals indicative of the intensity of the sensed X-ray photons.

[0110] In some embodiments, processor 22 may receive from detector 240 signals indicative of the intensity of a portion of beam 222 transmitted through surface 192 and

scattered from the HAR features of surface 191, also referred to herein as scattered signals.

[0111] In alternative embodiments, calibration gauge 215 may comprise one or more X-ray detectors, positioned to measure the Laue diffraction from planes substantially perpendicular to surfaces 191 and 192 of wafer 190, and to produce signals indicative of the intensity of the measured Laue diffraction, referred to herein as alternative diffraction signals.

[0112] In some embodiments, based on one or more of the diffraction signals described above, processor 22 is configured to instruct stage 210 to apply  $\omega$  and  $\chi$  rotations to wafer 190. Processor 22 may use a position of wafer 190 corresponding to a maximal intensity of the diffracted X-ray detected by detector 240, for establishing the inclination angles of beam 130 relative to the crystal lattice in wafer 190.

[0113] In these embodiments, processor 22 is configured to establish the inclination angle between the crystal lattice plane and the surface of wafer 190, by using measurements at two or more azimuths that satisfy the diffraction condition. Moreover, processor 22 may apply to beam 130 X-ray diffraction (XRD) methods, for determining the orientation of surfaces 191 and 192, as a calibration technique for non-X-ray based gauges. For example, calibration may be performed by measuring a reference wafer, or any suitable reference structure mounted on a carrier wafer or on the tool, with known inclination angles between the crystal lattice and surfaces 191 and 192.

[0114] In these embodiments, detector 240 may comprise various suitable types of detection elements, such as but not limited to, (a) arrays of 1D diodes made from silicon, germanium or CdTe or other suitable materials, and (b) 2D X-ray direct or indirect detection cameras that are based on CCD, CMOS sensors, PIN diodes, or hybrid pixel detector technologies.

[0115] In alternative embodiments, system 10 may comprise, in addition to calibration gauge 215, an energy dispersive X-ray (EDX) detector assembly (not shown). The EDX detector assembly comprises a silicon-based or a germanium-based solid-state EDX detector, and an electronic analyzer having a single-channel or multiple channels. The EDX detector assembly is configured to measure X-ray fluorescence emitted, for example, from point 111 of wafer 190, or from a predefined location of a reference wafer used for calibrating system 10, and to produce an electrical signal indicative of the intensity of X-ray fluorescence measured at point 11.

[0116] Based on the electrical signal, processor 22 is configured to determine a first position of point 111 and an offset between the first position and a second position acquired at the same time, by calibration gauge 215.

[0117] In some embodiments, X-ray source 100 and at least some of the x-ray optics between source 100 and wafer 190, are mounted on a first stage, wafer 190 is mounted on a second stage (e.g., stage 210) and at least one of optical microscope 50 and optical gauges 215 is mounted on a third stage. By comparing between the XRF-based and optical-based signals, processor 22 is configured to identify spatial offset, for example, between an optical pattern recognition camera of optical microscope 50, and X-ray beam 130, and to identify any misalignment between the aforementioned stages of system 10.

[0118] In some embodiments, processor 22 is configured to estimate, based on the received electrical signals, motion errors in stage 210, such as leadscrew errors and non-orthogonality between the x-axis and y-axis of stage 210. Furthermore, based on the X-ray fluorescence signals, processor 22 is configured to calibrate stage 210, which calibration is also referred to herein as stage mapping, by estimating offsets between one or more points in the coordinate system of system 10, and the actual positions of the respective points on stage 210.

[0119] In some embodiments, system 10 may comprise, in addition to or instead of the EDX assembly described above, a calibration scheme based on attenuation of the X-ray beam that passes through a suitable reference wafer (not shown), also referred to herein as a direct beam. The suitable reference wafer may comprise patterned features adapted to attenuate the direct beam intensity by several tens of percent, so that detector 240 could sense photons of the direct beam without being affected (e.g., saturated). In an exemplary embodiment, the reference wafer may comprise various patterns having any suitable thickness, e.g., about 50  $\mu\text{m}$ , of various suitable elements or alloys, such as but not limited to tungsten (W), tantalum (Ta), gold (Au) or silver (Ag).

[0120] In some embodiments, processor 22 may use calibration gauge 215 for aligning between beam 130 and wafer 190 during measurements of structures on product wafers, such as wafer 190, or for calibrating system 10, e.g., after performing maintenance operations so as to prepare system 10 for use in production.

[0121] In alternative embodiments described above, system 10 may comprise at least one calibration gauge 215 mounted at the opposite side of wafer 190 so as to measure the inclination of wafer 190 based on signals sensed from surface 191. In an embodiment, processor 22 is configured to calibrate an offset between the inclination angles measured on a blanket and the patterned area of a wafer.

[0122] In this embodiment, processor 22 positions calibration gauge 215 to direct the optical beam on a first point located adjacent to the edge of surface 191, which is typically blanket (i.e., without pattern), and measures the inclination of the wafer in x and y axes. Subsequently, processor 22 positions calibration gauge 215 to direct the optical beam at a second point on a pattern in the closest proximity (e.g., 10 mm-20 mm) to the first point, and measures the inclination of the wafer in x and y axes.

[0123] In some embodiments, based on the inclination measurements at the first and second points, processor 22 calculates the offset between the blanket and patterned surfaces. Note that the wafers are typically rigid, such that the actual inclination angle is not changing within a distance of 10 mm or 20 mm. The offset may be used as a calibration factor between inclination measurements on blanket and patterned surfaces of wafer 190 or any other type of measured wafer. In some embodiments, processor 22 may set the spot size of the optical beam to be sufficiently small to illuminate only the blanket surface near the wafer edge, but sufficiently large to average the inclination measurement over various features of the pattern.

[0124] In some embodiments, wafer 190 comprises a single-crystalline material, and at least one of XRD detectors 54 and 56 is configured to measure the diffraction of beam 220 from a lattice plane of the single-crystal material. In some embodiments, in response to the measured diffraction,

processor 22 is configured to calibrate suitable parameters (e.g., orientation) of calibration gauge 215 with respect to the lattice plane.

[0125] The particular configuration of calibration gauge 215 is shown in FIG. 1 schematically, so as to demonstrate calibration techniques for improving the measurements of features, such as HAR structures, of wafer 190, carried out by system 10. Embodiments of the present invention, however, are by no means limited to this specific sort of example configuration, and the principles of calibration gauge 215 described above, may be implemented using any suitable configuration.

[0126] In an embodiment, system 10 comprise a beam-blocking assembly, referred to herein as a beam blocker 230, made from an X-ray opaque or partially-opaque material.

[0127] Beam blocker 230 is mounted in system 10 between wafer 190 and detector 240, and is configured to occlude at least part of beam 220 from irradiating detector 240. In some cases at least part of incident beam 130 may be directly transmitted through wafer 190.

[0128] In some embodiments, beam blocker 230 may be positioned so as to partially block the directly-transmitted incident beam over an angular range comparable to the spatial extent of incident beam 130.

[0129] Example implementations of beam blockers are depicted in detail in FIGS. 7A and 7B below.

[0130] In some embodiments, the opaqueness level and shape of beam blocker 230 affect the signals produced by detector 240, as depicted in FIGS. 8A, 8B, 9A and 9B below.

[0131] In some embodiments, the detector assembly may comprise a single detector, or an array of detectors arranged around regions 226. The beam detectors may have a 2D configuration (i.e., an area detector), or a 1D configuration (i.e., a linear detector), and are capable of counting X-ray photons. Detector 240 may be flat, or may have any suitable shape such as an arc angled toward beams 222 and 220. Responsively to the captured photons, 240 is configured to generate electrical signals, which are conveyed, via interface 24, to processor 22. One example implementation of detector 240 is depicted in detail in FIG. 10 below.

[0132] In some embodiments, system 10 comprises a vacuum chamber 280, mounted between wafer 190 and detector 240 and configured to reduce undesired scattering of beam 220 from air. In some embodiments, vacuum chamber 280 comprises a metal tube with windows transparent to X-ray at each end, so that beams 220 and 222 can pass between wafer 190 and detector 240.

[0133] In some embodiments, system 10 comprises a suitable vacuum pump, such as a roughing pump controlled by processor 22, so as to control the vacuum level in vacuum chamber 280, thereby to improve signal-to-background (SBR) ratio of X-ray photons impinging on the active surface of detector 240.

[0134] In some embodiments, system 10 is configured to measure structural (e.g., dimensions and shape) as well as morphological parameters on the aforementioned features of wafer 190. For example, based on the electrical signals received from detector 240, processor 22 is configured to measure a large variety of parameters, such as but not limited to height, depth, width and sidewall angle of the patterned structure, and thickness and density of films at any location across wafer 190.

[0135] In some embodiments, processor 22 comprises a model-based software for analyzing the electrical signals



received from detector **240**. Processor **22** uses a single structural model so as to simulate the X-ray scattering for all incidence angles having a common intensity normalization factor. Subsequently, processor **22** compares the correlation between the measured and simulated intensity distributions, e.g., based on a numerical analysis of a goodness-of-fit (GOF) parameter.

[0136] In some embodiments, processor **22** is configured to iteratively adjust the parameters of the model, for example by using an algorithm such as Differential Evolution (DE), so as to minimize the GOF parameter and to obtain the best-fit model parameters.

[0137] In some embodiments, processor **22** may reduce the correlation between model parameters by introducing into the model parameter values measured by complementary techniques, for example the width at the upper layer of a feature in question measured by a critical dimension scanning electron microscope (CD-SEM).

[0138] In some embodiments, system **10** may comprise one or more calibration targets having arrays of periodic features externally characterized using any suitable reference technique other than SAXS, e.g., atomic force microscope (AFM). Processor **22** may use the calibration targets as a reference for calibrating the aforementioned assemblies of system **10** and for alignment between (a) beam **130** and wafer **190**, and (b) between beam **222** and detector **240**.

[0139] In some embodiments, based on the SAXS configuration and the software algorithms described above, system **10** is configured to detect disorder parameters in the features in question across wafer **190**. For example, horizontal and vertical roughness of the sidewalls and pitch variation, such as a pitch-walking error that may appear, for example, in multi-patterning lithography processes or tilting and twisting of the channel holes due to the etch process in 3D NAND memory.

[0140] In the context of the present disclosure and in the claims, the terms “small angle” and “small-angle” of the SAXS refer to an angle smaller than 10 degrees relative to the direct beam.

[0141] The configuration of system **10** is shown by way of example, in order to illustrate certain problems that are addressed by embodiments of the present disclosure and to demonstrate the application of these embodiments in enhancing the performance of such a system. Embodiments of the present invention, however, are by no means limited to this specific sort of example system, and the principles described herein may similarly be applied to other sorts of X-ray systems used for measuring features in any suitable type of electronic devices.

[0142] FIG. 2 is a schematic illustration of a SAXS system **30**, in accordance with another embodiment of the present invention. In some embodiments, the configuration of SAXS system **30**, also refers to herein as “system **30**” for brevity, is similar to the configuration of system **10** with wafer **190** tilted, also referred to herein as rotated, at any suitable angle (e.g., 45 degrees) relative to incident beam **130**.

[0143] In some embodiments, processor **22** is configured to instruct stage **210** to tilt wafer **190** about a tilt axis, such as azimuthal rotation  $\omega$  about y-axis, in a plane of wafer **190**, and to orient at least one of the aforementioned slit assemblies parallel to the tilt axis.

[0144] In some embodiments, system **30** is configured to measure structures of wafer **190** having a low aspect ratio (e.g., height over width ratio smaller than ten). As described

above, processor **22** is configured to rotate wafer **190** relative to incident beam **130**, or alternatively, to rotate incident beam **130** relative to wafer **190**. Processor **22** is configured to carry out the rotation over a range of several tens of degrees around y-axis, referred to herein as  $\omega$  rotation.

[0145] In some embodiments, the range of rotation angles may be symmetric, for example  $\pm 50$  degrees relative to the surface of wafer **190** shown, for example, in FIG. 1 above. In alternative embodiments, processor **22** may carry out asymmetric rotation (e.g.,  $-10$  degrees to  $+60$  degrees), for example by instructing stage **210** to rotate wafer **190** to a desired angle within the aforementioned range.

[0146] In some embodiments, processor **22** is configured to measure a profile of a structures in more than one plane, for example, by rotating the azimuth of wafer **190** relative to beam **130**. In the context of the present disclosure and in the claims, the term “profile” refers to a shape of a single sidewall of a measured feature, or a change of width between two adjacent sidewalls along the depth or height thereof or shift of the center of the hole as a function of depth. Additional asymmetry of the holes such as elliptical rather than circular cross section will usually require measurements at different azimuth and chi axes.

[0147] For example, processor **22** may measure the profile of a feature in a selected xy-plane using a series of intensity measurements carried out at different azimuthal angles. In some embodiments, processor **22** may implement this technique for measuring the diameter of a channel hole in a 3D NAND memory device, or the width of a via and/or metal line of local interconnect structures of a logic device.

[0148] In an embodiment, beam blocker **230** is positioned in close proximity to detector **240**. In another embodiment, beam blocker **230** may be positioned in close proximity to wafer **190**.

[0149] FIG. 3 is a schematic illustration of a SAXS system **40**, in accordance with another embodiment of the present invention. In some embodiments, the configuration of SAXS system **40**, also refers to herein as “system **40**” for brevity, is similar to the configuration of system **10** with beam blocker **230** positioned in close proximity to wafer **190**.

[0150] In some embodiments, processor **22** is configured to control the position of beam blocker **230** at any suitable position along the path of beam **220**, so as to reduce the level of undesired background and stray scattering sensed by detector **240**.

[0151] In some embodiments, processor **22** may set the position of beam blocker **230** at one or more predefined mounting locations along the path of beam **220**. Additionally or alternatively, processor **22** may adjust the position of beam blocker **230** by controlling a motorized stage (not shown) configured to move and hold beam blocker **230** at any suitable position between wafer **190** and detector **240**.

[0152] The structure of beam blocker **230** and related assemblies, such as the aforementioned stage, are described in detail, for example, in FIG. 7A below. Moreover, embodiments related to the functionality and applications of beam blocker **230** in measuring features in question of wafer **190** are described in detail in FIGS. 8B and 9B below.

[0153] The configurations of systems **10**, **30** and **40** are provided by way of example. Embodiments of the present invention, however, are by no means limited to this specific sort of example systems, and the principles described herein may similarly be applied to other sorts of metrology sys-

tems, such as but not limited to, reflection-based X-ray metrology systems having both the X-ray source and detector assemblies located at the same side of the wafer.

[0154] FIG. 4 is a schematic illustration of beam conditioning assembly 165, in accordance with an embodiment of the present invention. Beam conditioning assembly 165 may be used in any of systems 10, 30 and 40 described above, or in any other suitable configuration of a metrology system that applies X-ray beams for measuring features produced in wafer 190 or any other type of wafer.

[0155] In some embodiments, beam conditioning assembly 165 comprises multiple sets of slit assemblies, referred to herein as assemblies 110, 300 and 320. Note that as shown in FIGS. 1-3, assembly 110 may be external to beam conditioning assembly 165, or incorporated therein as shown in FIG. 4. Similarly, assembly 320 may be part of, or external to, beam conditioning assembly 165.

[0156] As described in FIG. 1 above, the slit assemblies of beam conditioning assembly 165 are configured to block undesired scattered X-ray radiation deflected from the designed optical path of beam 130, and/or to adjust the divergence, intensity and spot-size of beam 130.

[0157] In some embodiments, beam conditioning assembly 165 comprises mirror 120, which is configured to shape the optical properties of beam 130 after the beam passes through assembly 110, as described in FIG. 1 above.

[0158] In some embodiments, mirror 120 comprises a curved substrate 122 coated with multiple layers 124, for example, alternating thin (e.g., an order of one micron) layers of a heavy element, such as W, Mo or nickel (Ni), with a light element, such as carbon or silicon. Such mirrors for X-ray optics are provided by several suppliers, such as Incoatec GmbH (Hamburg, Germany), AXO DRESDEN GmbH (Dresden, Germany) or Xenocs (Sassenage, France). In some embodiments, the configuration of mirror 120 is adapted to provide a collimated beam in two directions (x,y). In other embodiments, mirror 120 is configured to collimate beam 130 in one direction (e.g., x-direction) and to focus beam 130 in an orthogonal direction (e.g., y-direction).

[0159] In some embodiments, mirror 120 is configured to focus beam 130 on surface 191, so as to obtain the smallest spot-size. In other embodiments, focusing the X-ray beam on detector 240 may provide system 10 with improved angular resolution of the X-ray beam sensed by detector 240, e.g., in imaging of the HAR structures.

[0160] In case of a 2D collimated beam, beam conditioning assembly 165 may comprise two optics, e.g., two mirrors 120, facing one another so as to increase the solid angle (i.e., a two-dimensional angle) collected from source 100 and to increase the X-ray flux of beam 130.

[0161] In some embodiments, beam conditioning assembly 165 may comprise any suitable configuration of multiple multilayered mirrors, such as mirror 120, mounted on one or more motorized actuators controlled by processor 22. Processor 22 may arrange the configuration of each mirror 120 of beam conditioning assembly 165, so as to obtain the most suitable measurement conditions by adjusting the optical properties of beam 130.

[0162] In some embodiments, beam conditioning assembly 165 comprises a crystal 310, made from a single crystal of germanium (Ge) or any other suitable material. Crystal 310 has a v-shaped channel 312 comprising an entrance aperture 316, an exit aperture 318, and opposing internal

faces 314 and 315 arranged so that channel 312 tapers from entrance aperture 316 to exit aperture 318, which is smaller than aperture 316.

[0163] In some embodiments, beam 130 passes through slit assembly 110 into mirror 120 and subsequently passes through slits assembly 300 and entrance aperture 316. Subsequently, beam 130 impinges on internal face 314 and thereafter on internal face 316 and exits crystal 310 through exit aperture 318.

[0164] In some embodiments, beam conditioning assembly 165 serves as a dispersing element, and additionally as beam compressing optic configured to reduce the spot size of beam 130 after exiting slit assembly 320 of assembly 165. The configuration of beam conditioning assembly 165 enables the beam compressing, and yet, reduces the loss of flux compared to alternative techniques, such as a crystal with a channel having parallel faces or using one or more slits having one or more narrow apertures.

[0165] In the example configuration of FIG. 4, slit assemblies 110, 300 and 320 are mounted before and after mirror 120 and crystal 310 so as to improve the shaping of beam 130 along the optical path described above. In other embodiments, beam conditioning assembly 165 may comprise any other suitable configuration of slit assemblies interposing between source 100 and mirror 120, and/or between mirror 120 and crystal 310, and/or between crystal 310 and slit assembly 140 or any other component or assembly of any of systems 10, 30 and 40. For example, slit assembly 320 may be removed from the configuration of assembly 165 and may be excluded from the configuration of any of systems 10, 30 and 40.

[0166] FIG. 5 is a schematic illustration of slit assembly 140, in accordance with an embodiment of the present invention. As shown in FIGS. 1-3, slit assembly 140, also referred to herein as a beam limiter, is positioned between source 100 and surface 192 of wafer 190, so as to intercept beam 130.

[0167] In some embodiments, slit assembly 140 comprises two or more movable plates 520 positioned along a translation axis 522 in a predefined distance from one another so as to define a slit 512. The distance between plates 520 may be controllable by processor 22, for example using one or more actuators (not shown) for moving one or more plates 520 along translation axis 522. Alternatively, the distance between plates 520 may be constant, e.g., by not moving plates 520 relative to one another, or by selecting a suitable type of slit 512 having static plates positioned at a desired distance from one another.

[0168] In some embodiments, slit assembly 140 comprises two or more movable blades 510A and 510B, which are not parallel to one another and have respective edges 514A and 514B positioned in close proximity to one another, so as to define a micro-slit 515.

[0169] In some embodiments, micro-slit 515 is configured to block part of beam 130 that impinges on blades 510A and 510B without producing scattered beams, thus blades 510A and 510B are also referred to herein as "anti-scatter blades." In some embodiments, blades 510A and 510B are made from single-crystal materials such as tantalum (Ta), Ge, indium-phosphide (InP), or from polycrystalline materials such as tungsten-carbide, and have a thickness of about 1 mm or any other suitable thickness.

[0170] In the context of the present disclosure, and in the claims, the terms “single-crystal” and “mono-crystal” are used interchangeably and refer to materials having a structure made from one crystal.

[0171] In some embodiments, slit assembly 140 comprises actuators 500A and 500B, configured to move respective blades 510A and 510B along respective translation axes 516A and 516B, so as to adjust the width of micro-slit 515. In an embodiment, at least one of translation axes 516A and 516B is substantially orthogonal to translation axis 522 in the x-y plane.

[0172] In some embodiments, actuators 500A and 500B comprise one or more piezoelectric linear motors, for example the Piezo LEGS Linear 6G series provided by PiezoMotor (Uppsala, Sweden) or similar products from other vendors such as Physik Instrumente (Karlsruhe, Germany). These motors can be supplied with integrated high-resolution position sensors.

[0173] In some embodiments, processor 22 is configured to position slit assembly 140 in any suitable proximity to surface 192 of wafer 190. The design of micro-slit 515 allows processor 22 to position slit assembly 140 such that at least one of edges 514A and 514B is positioned at a distance smaller than ten millimeters (10 mm) from surface 192. In other embodiments, processor 22 may position micro-slit 515 at any selected distance, e.g., between 100 mm and a few millimeters, from surface 192.

[0174] In some embodiments, the configuration of micro-slit 515 allows processor 22 to position slit assembly 140 in close proximity (e.g., down to a few millimeters) to surface 192 even when wafer 190 is tilted, as shown in FIG. 2 above.

[0175] In some embodiments, processor 22 is configured to set the distances between (a) micro-slit 515 and surface 192, (b) edges 514A and 514B, and (c) plates 520, so as to obtain the desired optical properties of beam 130 before impinging on surface 192 and interacting with the structures and bulk of wafer 190.

[0176] Reference is now made to an inset 502, which is a top view of the interception between slit assembly 140 and beam 130. In the example of inset 502, processor 22 is configured to change the spatial shape of beam 130 from a round shape of a circle 524, to a rectangular shape shown by a dashed rectangle 526, by moving (a) blades 510A and 510B along respective translation axes 516A and 516B, and (b) plates 520 along translation axis 522. Note that in this example, only the portion of beam 130 within the area of dashed rectangle 526 impinges on surface 192, whereas the remaining part of beam 130, located between the edges of circle 524 and dashed rectangle 526, is blocked by slit assembly 140. As described above and shown in inset 502, at least one of translation axes 516A and 516B is orthogonal to translation axis 522.

[0177] The configuration of slit assembly 140 is simplified for the sake of conceptual clarity and is provided by way of example. In other embodiments, slit assembly 140 may comprise more than two blades 510A and 510B, and/or more than two plates 520. Moreover, the edge of plates 520 and/or edges 514A and 514B may have any suitable shape, for example, both plates 520 and edges 514A and 514B may have an arc intruding into the area of the respective plates 520 and blades 510A and 510B, so as to form a round shape, rather than the aforementioned rectangular shape, of beam 130 exiting from slit assembly 140.

[0178] In other embodiments, translation axes 516A and 516B may be parallel or not-parallel to one another, and at least one of translation axes 516A and 516B may not be orthogonal to translation axis 522.

[0179] FIG. 6 is a schematic illustration of a slit assembly 150, in accordance with another embodiment of the present invention. Slit assembly 150 may replace, for example, slit assembly 140 shown in FIGS. 1-3.

[0180] In some embodiments, slit assembly 150 comprises a 3-pinhole collimation system, also referred to herein as apertures 604, 606 and 608, arranged along a translation axis 610 of a movable blade 550.

[0181] In some embodiments, slit assembly 150 comprises an actuator 600, configured to move blade 550 along translation axis 610.

[0182] Reference is now made to an inset 602, which is a top view of an interception between beam 130 and blade 550. In some embodiments, each aperture 604, 606 and 608 comprises a fixed size apertures, such as a SCATEX scatterless pinhole produced by Incoatec GmbH (Hamburg, Germany). In the example of blade 550, apertures 604, 606 and 608 have a round shape and each aperture has a different diameter, e.g., between about 20  $\mu\text{m}$  and 500  $\mu\text{m}$ .

[0183] In some embodiments, blade 550, which serves as a frame of the scatterless pinholes, is made from Ge for X-ray beams having low energy of photons, or from Ta for beams having photons with higher energies.

[0184] In some embodiments, the configuration of apertures 604, 606 and 608 is adapted to reduce undesired parasitic scattering typically occurs when an X-ray beam passes through other types of apertures.

[0185] In some embodiments, actuator 600 may comprise any suitable type of motor coupled to a drive rod 620, which is configured to move blade 55 along translation axis 610.

[0186] In other embodiments, the configuration of actuator 600 may be similar to the configuration of actuators 500A and 500B described in FIG. 5 above.

[0187] In some embodiments, processor 22 is configured to determine the optical properties of beam 130 by instructing actuator 600 to position a selected aperture of blade 550 to intercept beam 130. In the example of FIG. 6, actuator 600 positions aperture 606 so that beam 130 passes therethrough, and the portion of beam 130 that exceeds the area within aperture 606 will be blocked.

[0188] FIG. 7A is a schematic illustration of beam blocker 230, in accordance with an embodiment of the present invention. In some cases, at least part of incident beam 130 that impinges on surface 192 is transmitted directly through wafer 190 and exits from surface 191, as part of beam 220, without being scattered. The directly transmitted part of beam 220 is referred to herein as a “direct beam.”

[0189] In some embodiments, beam blocker 230 is positioned so as to attenuate the X-ray radiation of the direct beam, typically at the center of beam 220. This attenuation is necessary, for example, to prevent damage to detector 240 and/or to prevent the detector from saturation and from operating in a non-linear region. On the other hand, too large attenuation would eliminate the detection of essential signals that may be used by processor 22 for tracking the angular position and intensity of the center of beam 220. Thus, the attenuation of beam blocker 230 is typically selected so that the intensity of the transmitted beam is attenuated to a few hundreds or thousands of photons per second at detector 240.

[0190] In some embodiments, beam blocker 230 comprises one or more beam blocking elements, such as a beam stopper 232, typically having an ellipsoidal-shape or any other suitable shape. In some embodiments, beam stopper 232 is made from an X-ray partially-opaque material, also referred to as high-Z materials, typically comprising metal elements, such as tantalum or tungsten, and/or any suitable metal alloys.

[0191] As described above, the attenuation of beam stopper 232 is selected to enable reliable measurement of the angular position and intensity of beam 220, and at the same time prevent damage and non-linear distortion in the sensing of detector 240.

[0192] In some embodiments, beam stopper 232 is further configured to minimize background intensity from sources such as scattering with air or fluorescence and other scattering from the electronics behind the active region or surface of detector 240. Note that the active region of detector 240 may be partially illuminated due to the limited thickness or low absorption of the detector material, e.g. 450  $\mu\text{m}$  of silicon, with high energy X-rays having an energy of 10 keV or higher.

[0193] In some embodiments, beam stopper 232 has a curvy and/or smooth edge so as to reduce the scattering intensity of the direct beam.

[0194] In some embodiments, beam blocker 230 comprises a matrix 236, also referred to herein as a mount. Matrix 236 is made from a block of material adapted not to scatter X-rays, such as, but not limited to, diamond or polymers such as thin-sheets of biaxially-oriented polyethylene terephthalate (BoPET) polyester, also referred to herein as Mylar™, or poly (4,4'-oxydiphenylene-pyromellitimide) polyimide, also referred to herein as Kapton®.

[0195] In some embodiments, beam stopper 232 is mounted in a recess (not shown) formed in a matrix 236, and is mechanically supported by the matrix material without using an adhesive that may scatter X-rays, and therefore, may increase the level background signals to the measurements. Since adhesives may degrade under X-ray irradiation with time, absorbing features can be fabricated using techniques used for electronics manufacturing such as depositing thin adhesion and seed layers with appropriate metalization and then electroplating a thick X-ray absorbing material such as gold (Au), or by using of additive printing techniques using inks incorporating a high concentration of metallic nanoparticles followed by an annealing process.

[0196] In other embodiments, beam stopper 232 may be coupled to matrix 236 using any other suitable technique, such as an adhesive that does not scatter X-rays. Note that beam stopper 232 is adapted to attenuate the direct beam, such that the surrounding scattered beam, shown in FIG. 1 as beam 222, is not attenuated since the support structure is transparent to the scattered X-rays of beam 222.

[0197] In some embodiments, the material of beam stopper 232 allows sufficient intensity of the direct beam to be partially transmitted, so that processor 22 may determine the intensity and position of the direct beam sensed by detector 240 without moving beam stopper 232 away from the direct beam.

[0198] In some embodiments, beam blocker 230 comprises a mount, also referred to herein as a high-precision motorized stage 233, which is controlled by processor 22 and is configured to move along one or more axes. For

example translation x-axis and y-axis in the configuration of systems 10 and 30 shown, respectively, in FIGS. 1 and 2 above.

[0199] In some embodiments, matrix 236 is mounted on stage 233 so that processor 22 sets the position of beam stopper 232 relative to the direct beam transmitted through wafer 190. In other embodiments, stage 233 may comprise rotational axes (not shown) so as to improve the alignment of beam stopper 232 with beam 220, and particularly with the direct beam thereof. In another embodiment, stage 233 is also configured to move in z-axis so as to enable the configuration of system 40, shown in FIG. 3 above, or to further improve the attenuation level of the direct beam.

[0200] In some cases, the attenuation of the direct beam may be sufficiently high by wafer 190 or by any other element of system 10. Thus, in other embodiments, processor 22 is configured to move beam blocker 230 away from the path of beam 220. In these embodiments, beam stopper 232 is not intercepting beam 220, so that processor 22 may monitor the intensity and position of the direct X-ray beam, based on the direction and intensity of the direct beam sensed by detector 240.

[0201] The configuration of beam blocker 230 is simplified for the sake of conceptual clarity and is provided by way of example. In other embodiments, beam blocker 230 may comprise any other suitable components and/or assemblies arranged in any other suitable configuration for attenuating the intensity of the direct beam and/or for managing the sensing of one or more beams 222 scattered from wafer 190. For example, the beam-blocker may comprise multiple beam stoppers 232, or two narrow wires whose separation can be adjusted so as to change the effective width of the blocker.

[0202] FIG. 7B is a schematic illustration of beam blocker 330, in accordance with an embodiment of the present invention. Beam blocker may replace, for example, beam blocker 230 of FIG. 1 above. In some embodiments, beam blocker 330 comprises a matrix 333 made from a synthetic diamond, or the materials of matrix 236 described above, or any other suitable material adapted not to scatter X-rays of beam 220.

[0203] In some embodiments, beam blocker 330 comprises multiple types of beam stoppers, each of which made from a suitable material. For example, a gold-based beam stopper having a thickness of about 50  $\mu\text{m}$ , or any other suitable thickness, or a tungsten-based beam stopper having a typical thickness between 50  $\mu\text{m}$  and 100  $\mu\text{m}$ , or any other suitable thickness. The tungsten-based beam stopper may be produced, for example, by laser cutting of a suitable tungsten foil.

[0204] In some embodiments, the beam stoppers are coupled to matrix 333, using any suitable technique, such as recessing the matrix and disposing the beam stopper into the recessed pattern, or any other suitable method, such as those described in FIG. 7A above. For example, gold or tantalum may be deposited into the recessed pattern or deposited using chemical and/or physical techniques on the surface of the matrix, and the laser-cut tungsten pieces, described above, may be attached to the recessed pattern.

[0205] In some embodiments, beam blocker 330 comprises multiple geometric shapes and arrangements of beam stoppers. In the example of FIG. 7B, beam blocker 330 comprises five bar-shaped beam stoppers arranged in a row along X-axis, at a 5 mm distance from one another, and

having a similar length (measured along Y-axis) of about 10 mm. The bar-shaped beam stoppers have different width, e.g., between 0.1 mm and 0.5 mm. For example, beam stoppers **332** and **334** have a width (measured along X-axis) of about 0.5 mm and 0.3 mm, respectively, and the bar between beam stoppers **332** and **334** has a width of about 0.4 mm.

[0206] In some embodiments, beam blocker **330** comprises five square-shaped beam stoppers having the same arrangement along X-axis (e.g., width and distance) of the bar-shaped beam stoppers described above. For example, beam stoppers **336** and **338** have widths of 0.4 mm and 0.2 mm, respectively, and the square-shaped beam stopper laid out therebetween has a width of 0.3 mm.

[0207] In some embodiments, beam blocker **330** may comprise other shapes of beam stoppers such as rectangular, elliptical shapes. Beam blocker **330** may comprise additional marks to assist with alignment of the blocker, such as marks **337** and **339**.

[0208] The configuration of beam blocker **330** is provided by way of example. In other embodiments, beam blocker **330** may comprise any other set of beam stoppers, having any suitable shape and dimensions and arranged in any suitable layout.

[0209] FIG. 8A is a schematic illustration of an image **402** indicative of the intensity of beam **220** sensed by detector **240** in the absence of beam blocker **230**, in accordance with another embodiment of the present invention. In the example of FIG. 8A, incident beam **130**, which is collimated in both x-axis and y-axis, impinges on wafer **190** comprising a hexagonal array of features, such as HAR capacitors of a DRAM device.

[0210] In some embodiments, image **402** comprises a spot **420**, indicative of the intensity of the direct beam sensed by detector **240**. Image **402** further comprises multiple spots **410**, indicative of respective beams **222** scattered from the hexagonal array of the DRAM device. In some embodiments, the gray level of spots **410** and **420** is indicative of the intensity of beam **220** (e.g., flux of photons and respective energy thereof) sensed by detector **240**. In the present example, white color is indicative of high intensity, and darker colors indicative of lower intensities sensed by detector **240**.

[0211] In some embodiments, image **402** comprises locations **404** positioned between spots **410** and spot **420**, within region **226** of detector **240**, also shown in FIG. 1 above. Image **402** further comprises a region **400**, referred to herein as a background, located out of region **226** of detector **240**.

[0212] In some embodiments, processor **22** is configured to set the properties of beam **130**, such that (a) spots **410** have coherent scattering, and therefore appear bright, (b) locations **404** between spots **410** have incoherent scattering, and therefore appear darker than spots **410** located within a virtual circle **405** surrounding an area in close proximity to spot **420**, and (c) region **400** has no scattering, or a scattering level below a predefined threshold, and therefore appears in black.

[0213] In some embodiments, in the absence of beam blocker **230**, the high intensity of the direct beam causes saturation of detector **240** at the area of spot **420**, and therefore, non-linear sensing across region **226**. Therefore, spot **420** appears in white color and the area within circle **405** appears substantially brighter than the peripheral area of region **226**.

[0214] As described above, due to the coherent scattering, spots **410** appear brighter than locations **404** within the area of circle **405**. However, due to the increase in the incoherent background from detector **240**, spots **410** appear darker than locations **404** at the periphery of region **226**. Thus, the reliable sensing area of detector **240** is limited to the area within circle **405**, subject to the limited contrast caused by the increased background (incoherently X-ray intensity) from detector **240**.

[0215] FIG. 8B is a schematic illustration of an image **406** indicative of the intensity of beam **220** sensed by detector **240** in the presence of beam blocker **230**, in accordance with an embodiment of the present invention. Similar to the example of FIG. 8A, incident beam **130**, which is collimated in both x-axis and y-axis, impinges on wafer **190** comprising the hexagonal array HAR capacitors of the aforementioned DRAM device.

[0216] In some embodiments, image **406** comprises a spot **430**, indicative of the intensity of the direct beam sensed by detector **240**. Image **406** further comprises multiple spots **440**, indicative of respective beams **222** scattered from the hexagonal array of the DRAM device.

[0217] In some embodiments, beam blocker **230** attenuates the intensity of the direct beam sensed by detector **240**, therefore, spot **430** appears in a dark gray color and detector **240** does not introduce a significant background intensity shown, for example, in FIG. 8A above.

[0218] In some embodiments, the sensed intensity of the coherent scattering from the HAR features appears stronger within circle **405** compared to the periphery of region **226**. Yet, the linear sensing of detector **240** reduces the intensity detected from locations **404** to the background level of region **400**. Thus within region **226**, the contrast between all spots **440** and regions **404** is sufficiently high to conduct measurements at high accuracy and precision. The term “accuracy” refers to measuring the actual size of the feature in question, and the term “precision” refers to the repeatability of multiple measurements carried out on a given feature in question.

[0219] In some embodiments, the presence of beam blocker **230** allows processor **22** to monitor the partially attenuated direct beam (e.g., during the measurements of the HAR structures) so as to control parameters indicative of the properties of beams **130** **220**, such as the incident flux of both beams **130** and **220** at respective positions on wafer **190** and detector **240**.

[0220] FIG. 9A is a schematic illustration of an image **502** indicative of the intensity of beam **220** sensed by detector **240** in the absence of beam blocker **230**, in accordance with another embodiment of the present invention. In the example of FIG. 9A, incident beam **130**, which is collimated in x-axis and focused on wafer **190** (e.g., on surface **191**) in y-axis, impinges on wafer **190** comprising an array of 1D (lines) or long and narrow 2D features, such as lines or trenches in a device or dedicated metrology pad in the scribe-line or elsewhere on die.

[0221] In some embodiments, image **502** comprises a spot **526**, indicative of the intensity of the direct beam sensed by detector **240**. Image **502** further comprises multiple features **510**, indicative of respective beams **222** scattered from the array. In some embodiments, the gray level of features **510** and spot **526** is indicative of the intensity of beam **220** sensed by detector **240**. As described in FIG. 8A above,

white color is indicative of high intensity, and darker colors indicative of lower intensities sensed by detector 240.

[0222] In some embodiments, image 502 comprises locations 504 positioned between features 510 and spot 526, within region 226 of detector 240. Image 502 further comprises region 400, located out of region 226 of detector 240.

[0223] In some embodiments, processor 22 is configured to set the properties of beam 130, such that features 510 have coherent scattering, locations 504 have incoherent scattering, and region 400 has no scattering.

[0224] In some embodiments, in the absence of beam blocker 230, the high intensity of the direct beam causes sufficiently high background intensity and loss of contrast across region 226. Therefore, spot 526 appears in white color and the area within a virtual rectangle 505 appears substantially brighter than the peripheral area of region 226.

[0225] As described above, due to the coherent scattering, features 410 appear brighter than locations 504 within the area of circle 405. However, the increased background from detector 240, results in loss of contrast at the periphery of region 226. Thus, the reliable sensing area of detector 240 is limited to the area within rectangle 505. Note that in the absence of beam blocker 230, the shape and size of the reliable sensing area of detector 240 depends on the type (e.g., geometry) of the measured features (e.g., round in FIG. 8A and linear in FIG. 9A), the properties of beam 130, and other parameters of the system, such as the tilt angle of wafer 190 shown, for example, in system 30 of FIG. 2 above.

[0226] FIG. 9B is a schematic illustration of an image 506 indicative of the intensity of beam 220 sensed by detector 240 in the presence of beam blocker 230, in accordance with an embodiment of the present invention. In some embodiments, processor 22 sets incident beam 130 in a like manner to the setting described in FIG. 9A above. Therefore, beam 130, which is collimated in x-axis and focused in y-axis, impinges on wafer 190 comprising the aforementioned layout of the lines or trenches.

[0227] In some embodiments, image 506 comprises a spot 530, indicative of the intensity of the direct beam sensed by detector 240. Image 506 further comprises multiple features 540, indicative of respective beams 222 scattered from the array of the NAND flash memory device.

[0228] In some embodiments, beam blocker 230 attenuates the intensity of the direct beam sensed by detector 240, therefore, spot 530 appears in a dark gray color and detector 240 is not saturated by excess intensity.

[0229] In some embodiments, the sensed intensity of the coherent scattering from the lines or trenches, appears stronger within rectangle 505 compared to the periphery of region 226. Yet, the linear sensing of detector 240 reduces the intensity detected from locations 504 to the background level of region 400. Thus within region 226, the contrast between all features 540 and regions 504 is sufficiently high to conduct measurements at high accuracy and precision.

[0230] As described in FIG. 8B above, the presence of beam blocker 230 allows processor 22 to monitor the partially attenuated direct beam so as to control parameters indicative of the properties of beams 130 220.

[0231] FIG. 10 is a schematic illustration of a scanning scheme in which detector 240 comprising an array of sensors 243 is moved at steps smaller than the inter-distance of the sensors, for improved angular resolution, in accordance with an embodiment of the present invention. In some embodiments, detector 240 comprises an array of 1D or 2D

sensor elements, referred to herein as sensors 243. In the example of FIG. 10 detector 240 comprises 2D sensors 243, each of which has a predefined pitch in x-axis and in y-axis, referred to herein as Px and Py, respectively.

[0232] In the context of the present disclosure, and in the claims, the terms “Px” and “width axis” are used interchangeably, and the terms “Py” and “height axis” are also used interchangeably. In some embodiments, each sensor 243 is configured to produce electrical signals indicative of the intensity of the direct beam and of beam 222 impinging on the active surface thereof. In some embodiments, processor 22 is configured to produce an image, referred to herein as a pixel, based on the electrical signals received from each sensor 243. Thus, the size of each pixel in x and y axes is typically on an order of Px and Py, respectively.

[0233] In some embodiments, detector 240 is mounted on a motorized stage 246 comprising translation and rotation motors (not shown). In some embodiments, the translation motors are configured to move detector 240 in x-axis and y-axis for scanning in the x-y plane, and in z-axis for improving the focus of beam 222 on the active surface of sensors 243. In some embodiments, the translation motors are configured to rotate detector 240, for example about z-axis, for aligning sensors 243 with the direction of the scattered X-ray photons of beam 222.

[0234] In some embodiments, stage 246 comprises high-precision encoders and/or interferometers (not shown) configured to measure the translation and rotation positions of the respective axes of stage 246 at a predefined frequency.

[0235] In some embodiments, system 10 may comprise a motion control assembly (not shown), which is controlled by processor 22. The motion control assembly comprises a controller (not shown) configured to determine, for each motor, a respective motion profile (e.g., speed, acceleration and deceleration). The motion control assembly further comprises one or more drivers, which are controlled by the aforementioned controller and are configured to drive the motors of stage 246 to move in accordance with the respective motion profile and based on the current position measured by the respective encoder or interferometer of each axis.

[0236] In other embodiments, processor 22 is further configured to control the motion of stage 246, and may be used for this purpose, in addition to or instead of the controller.

[0237] In some embodiments, stage 246 is configured to move detector 240 along x-axis and y-axis in selected respective step sizes, referred to herein as Dx and Dy, which are typically substantially smaller than respective Px and Py. Thus, stage 246 is configured to move detector 240 in steps equal to a fraction of the pixel size described above.

[0238] Equations 1 and 2 below provide explicit expressions for estimating the size of Dx and Dy, respectively:

$$Dx = p_x / m \quad (1)$$

$$Dy = p_y / n \quad (2)$$

[0239] where n and m are typically integer numbers indicative of the selected step size in x-axis and y-axis, respectively.

[0240] In some embodiments, processor 22 is configured to receive the electrical signals produced by a given sensor 243, and to set the rotation speed of wafer 190 in response to the received signals. Note that the acquisition time of sensor 243 inversely depends on the intensity of the sensed

X-rays. For example, if the electrical signals received at a given area of wafer 190 are indicative of a relatively low intensity of the sensed X-rays, processor 22 may instruct the controller to decelerate the motion of detector 240 at the given area so as to increase the flux of photons and thereby to increase the SBR sensed at the given area.

[0241] Similarly, in case of a relatively high intensity of the sensed X-rays at different rotation angles of wafer 190, processor 22 may instruct the controller to accelerate the motion of detector 240 at the different area so as to increase the measurement throughput.

[0242] In some embodiments, processor 22 or a controller of detector 240 is configured to control the acquisition time so that detector 240 received a predefined intensity range across the measured positions on wafer 190. The predefined intensity range enables sufficient intensity to obtain high SBR, and yet, prevents saturation and non-linear sensing in the respective sensors of detector 240.

[0243] In some embodiments, processor 22 is configured to acquire, from a given sensor 243, an image based on the intensity of the scattered photons of beam 222, at an acquisition time, t. Therefore, in an array of an n-by-m sub-pixels, processor 22 allocates for each sub-pixel a uniform time interval of  $t/(m \times n)$ , so as to acquire n-by-m sub-images within the acquisition time t.

[0244] In some embodiments, processor 22 is configured to move detector 240 in a raster pattern along the x and y axes using respective step sizes Dx and Dy, so as to measure the intensity distribution of each time interval at a different position of detector 240 spanning the total area of a single pixel.

[0245] In some embodiments, processor 22 is configured to combine the n-by-m sub-images received from the respective sensor 243, into a single pixel. Processor 22 may apply to the received sub-images any suitable method, such as but not limited to, a simple arithmetic interpolation, or any suitable image processing algorithms, so as to increase the resolution (e.g., angular resolution) of the combined image.

[0246] In some embodiments, by applying the sub-pixel stepping and combining the n ° m sub-images to form a single image having improved angular resolution, processor 22 overcomes a resolution limitation of SAXS systems caused by the available pixel size of the respective detector assembly.

[0247] Equation (3) below provides an expression for calculating the angular resolution A of a detector having a pixel size p, positioned at a distance d from the wafer in question:

$$\Delta\theta = p/d \quad (3)$$

[0248] Based on a typical pixel size of 172 um a distance of about 5-6 meters is required to obtain an angular resolution on an order of 0.3 mrad-0.5 mrad.

[0249] In some embodiments, by using the sub-pixel stepping and combining the nxm sub-images, as described above, the designed distance between detector 240 and wafer 190 may be reduced, for example by a factor of three, e.g., to less than two meters, while maintaining the required angular resolution.

[0250] In some embodiments, processor 22 is configured to reduce the overall cycle time of measuring the features in question of wafer 190 by increasing the speed of detector

240 to the maximal level that enables acquiring the sub-images at sufficiently-high SBR as will be described in detail hereinbelow.

[0251] The intensity of scattered beam 222 typically depends on the Fourier transform of the electron density distribution  $\rho(r)$  of the scattering objects. For weak scattering, the scattered amplitude “A” may be calculated using equation (4):

$$A(Q) \propto \int_V \rho_e(r) \exp(-iQ \cdot r) dr \quad (4)$$

[0252] where Q is the scattering vector and is determined by X-ray wavelength  $\lambda$  and the respective angles of incident beam 130 and scattered beam 222 relative to wafer 190.

[0253] Equation (5) below provides a well-known expression for calculating the scattered intensity in the kinematical approximation:

$$I(Q) = (A(Q))^2 + I_b(Q) \quad (5)$$

[0254] where  $I_b(Q)$  is an incoherent “background” intensity contribution system of any origin such as fluorescence or scattering from structures in the wafer beyond the coherence length of the radiation or parts of the tool, i.e. slits or beam blocker.

[0255] The electron density  $\rho_e$  is related to a refractive index “n” of the scattering objects of wafer 190. Equation (6) below provides an expression for calculating the refractive index n:

$$n = 1 - \delta - i\beta \quad (6)$$

[0256] Where  $\delta$  and  $\beta$  are, respectively, the dispersive and absorptive components of the wave-matter interaction.

[0257] Note that the value of the refractive index is close to unity for all materials in the range of hard X-rays, where the value of  $\delta$  is on the order of  $10^{-6}$ .

[0258] Therefore, equation (7) below may be used for calculating the electron density  $\rho_e$ :

$$\rho_e = \frac{2\pi}{\lambda^2 r_e} \delta \quad (7)$$

[0259] where  $r_e$  is the value of a classical electron radius, equals to  $2.818 \times 10^{-15}$  meters.

[0260] In some embodiments, processor 22 is configured to calculate a physical model comprising the topography and the materials of the features in question described above. Processor 22 is configured to compare between the calculated and measured intensities using any suitable parameters, such as a numerical goodness-of-fit (GOF), and to adjust the model parameters so as to minimize the different between the calculated and measured data.

[0261] The dataset fitted by processor 22 may comprise one or more 1D datasets, such as the intensity distribution integrated along or across the diffraction peaks for different orientations of beam 130 and/or detector 240 relative to wafer 190, or a series of 2D images of the scattered intensity patterns or a combination thereof.

[0262] As described above, processor 22 is configured to reduce the measurement time of the features in question by acquiring data using different acquisition times at different locations across wafer 190. In some embodiments, processor 22 may apply the different acquisition time by detector 240 in various conditions. For example, when measuring different type of features (e.g., geometrical structure and/or mate-

rials), and/or layout (e.g., a single feature, or a dense array of features), and/or the angle between beam **130** and surface **192** of wafer **190**, and/or the angle between beam **222** and the active surface of detector **240**.

**[0263]** In some embodiments, processor **22** is configured to adjust the signal acquisition time so as to obtain sufficient intensity that enables sufficiently high SBR of the electrical signals received from detector **240**. The measurement uncertainty of scattered X-ray having an average intensity based on  $N$  counts is typically dictated by Poisson counting statistics such that the standard error is given by  $\sqrt{N}$  and the fractional error is given by  $1/(\sqrt{N})$ . Therefore, processor **22** may reduce the measurement uncertainty by increasing the number of counts.

**[0264]** As described above, processor **22** may reduce the acquisition time at some locations, where the intensity of beam **222** sensed by detector **240** is high, and increase the acquisition time at other locations, where the intensity of the sensed X-rays is lower, so as to obtain sufficient, but not excess, of X-ray photon counting statistics.

**[0265]** In alternative embodiments, processor **22** may apply pre-processing, such as down-sampling and principal component analysis (PCA), to raw electrical signals received from detector **240**, such as 1D intensity profiles and/or 2D images for one or more rotation angles. Subsequently, processor **22** may apply one or more machine learning algorithms to the pre-processed data and to complementary data that can be used for assessing the value of the data, such as electrical test data of (e.g., of the features in question).

**[0266]** In these embodiments, processor **22** may use any suitable types of machine learning algorithms, such as the TensorFlow open-source machine learning framework initially developed by Google (Mountain View, Calif.), as training decks for deep learning using neural networks.

**[0267]** Processor **22** may subsequently apply the trained model obtained based on a preceding dataset, to data measured on subsequent wafers **190**, so as to predict the electrical performance of the respective device under test, or to provide a user of systems **10**, **30** and **40**, other useful attributes based on the data measured on the subsequent wafers **190**. Note that using the embodiments of such machine learning algorithms may require high sampling so as to develop reliable regression-based models.

**[0268]** In some embodiments, detector **240** comprises electronic circuitries (not shown) configured to discriminate between low-energy and high-energy photons of beam **220**. In some embodiments, processor **22** is configured to reduce the background intensity caused, for example, by X-ray fluorescence and high-energy cosmic rays.

**[0269]** In other embodiments, processor **22** is configured to remove many of the high-energy cosmic rays using software-based filters in combination with the sub-pixel resolution enhancement described above. In these embodiments, detector **240** may not include the hardware-based cosmic ray discrimination described above.

**[0270]** Although the embodiments described herein mainly address X-ray analysis of single-crystal, polycrystalline or amorphous samples, such as semiconductor wafers, the methods and systems described herein can also be used in other technological applications of arrays of nanostructures.

**[0271]** It will thus be appreciated that the embodiments described above are cited by way of example, and that the

present invention is not limited to what has been particularly shown and described hereinabove. Rather, the scope of the present invention includes both combinations and sub-combinations of the various features described hereinabove, as well as variations and modifications thereof which would occur to persons skilled in the art upon reading the foregoing description and which are not disclosed in the prior art. Documents incorporated by reference in the present patent application are to be considered an integral part of the application except that to the extent any terms are defined in these incorporated documents in a manner that conflicts with the definitions made explicitly or implicitly in the present specification, only the definitions in the present specification should be considered.

**1. X-ray apparatus, comprising:**

a mount, which is configured to hold a planar sample;  
an X-ray source, which is configured to direct a beam of X-rays toward a first side of the sample;

a detector, which is positioned on a second side of the sample, opposite the first side, so as to receive at least a part of the X-rays that have been transmitted through the sample; and

a beam limiter, which is positioned on the first side of the sample so as to intercept the beam of the X-rays, and which comprises:

first and second blades, having respective first and second edges positioned in mutual proximity so as to define a slit, through which the beam of the X-rays will pass, at a distance smaller than 25 mm from the first side of the sample; and

first and second actuators, which are configured to shift the first and second blades along respective, first and second translation axes so as to adjust a width of the slit.

**2. The apparatus according to claim 1, wherein the mount is configured to tilt the sample about a tilt axis in a plane of the sample, and wherein the slit is oriented parallel to the tilt axis.**

**3. The apparatus according to claim 1, wherein the first and second blades comprise a material made from a single-crystalline material or a polycrystalline material.**

**4. The apparatus according to claim 1, wherein the first and second blades are not parallel to one another.**

**5. The apparatus according to claim 1, wherein the first and second translation axes are not parallel to one another.**

**6. The apparatus according to claim 1, wherein the beam limiter is configured to control at least one beam parameter, selected from a list consisting of (i) a position of the beam, (ii) a spot size of the beam, (iii) a spot shape of the beam on the first side of the sample, and (iv) a convergence or divergence angle of the beam.**

**7. The apparatus according to claim 1, wherein the beam limiter is mounted on a stage, which is configured to move the beam limiter relative to at least one of the beam and the sample.**

**8. The apparatus according to claim 7, wherein the stage comprises at least a rotation stage.**

**9. The apparatus according to claim 1, wherein at least one of the first and second actuators comprises one or more piezoelectric linear motors.**

**10. The apparatus according to claim 1, and comprising first and second movable plates having respective first and second plate edges positioned in mutual proximity so as to**



define an additional slit, through which the beam of the X-rays will pass, before or after passing through the slit.

**11.** The apparatus according to claim **10**, and comprising a third actuator, which is configured to shift at least one of the first and second movable plates along a third translation axis so as to adjust a size of the additional slit.

**12.** The apparatus according to claim **10**, and comprising a processor, which is configured to shape the beam of the X-rays by aligning a position of the slit and the additional slit relative to one another.

**13.** A method, comprising:

holding a planar sample on a mount;

directing a beam of X-rays from an X-ray source toward a first side of the sample;

receiving, from a detector positioned on a second side of the sample, opposite the first side, at least a part of the X-rays that have been transmitted through the sample;

positioning on the first side of the sample a beam limiter so as to intercept the beam of the X-rays, the beam limiter comprising first and second blades, having respective first and second edges positioned in mutual proximity so as to define a slit, through which the beam of the X-rays will pass, at a distance smaller than 25 mm from the first side of the sample, and first and second actuators; and

adjusting a width of the slit by shifting the first and second blades along respective first and second translation axes, using the first and second actuators.

**14.** The method according to claim **13**, wherein holding the planar sample comprises tilting the sample about a tilt axis in a plane of the sample, and orienting the slit parallel to the tilt axis.

**15.** The method according to claim **13**, wherein the first and second blades comprise a material made from a single-crystalline material or a polycrystalline material.

**16.** The method according to claim **13**, wherein adjusting the width comprises positioning the first and second blades not parallel to one another.

**17.** The method according to claim **13**, wherein adjusting the width comprises shifting the first and second blades along the first and second translation axes that are not parallel to one another.

**18.** The method according to claim **13**, wherein adjusting the width comprises controlling at least one beam parameter, selected from a list consisting of (i) a position of the beam, (ii) a spot size of the beam, (iii) a spot shape of the beam on the first side of the sample, and (iv) a convergence or divergence angle of the beam.

**19.** The method according to claim **13**, wherein positioning the beam limiter comprises mounting the beam limiter on a stage for moving the beam limiter relative to at least one of the beam and the sample.

**20.** The method according to claim **19**, wherein moving the beam limiter comprises rotating the beam limiter.

**21.** The method according to claim **13**, wherein at least one of the first and second actuators comprises one or more piezoelectric linear motors.

**22.** The method according to claim **13**, and comprising defining an additional slit through which the beam of the X-rays will pass before or after passing through the slit, by positioning in mutual proximity first and second plate edges of first and second respective movable plates.

**23.** The method according to claim **22**, and comprising adjusting a size of the additional slit by shifting at least one of the first and second movable plates along a third translation axis.

**24.** The method according to claim **22**, and comprising shaping the beam of the X-rays by aligning a position of the slit and the additional slit relative to one another.

**25.** An X-ray optical device, comprising:

a crystal containing a channel having an entrance aperture, an exit aperture, and opposing internal faces arranged so that the channel tapers from the entrance aperture to the exit aperture;

an X-ray mirror, comprising a curved substrate with a multilayer coating, which is configured to collect and direct a beam of X-rays emitted from a source into the entrance aperture of the channel with a first beam diameter, so that the beam is emitted from the exit aperture with a second beam diameter, less than the first beam diameter; and

one or more slits interposed between the X-ray mirror and the crystal, so that the beam passes through the slits before entering the entrance aperture of the channel.

**26.** The device according to claim **25**, wherein the X-ray mirror is configured to adjust a divergence and intensity of the beam.

**27.** The device according to claim **25**, and comprising:

a blade having an array of apertures of different, respective sizes passing therethrough; and

an actuator, which is configured to position the blade in a path of the beam emitted from the exit aperture of the crystal and to translate the blade so as to position different ones of the aperture in the path.

**28.** The device according to claim **25**, wherein the crystal comprises a single-crystal made from germanium.

**29.** The device according to claim **25**, wherein the opposing internal faces are not parallel to one another.

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