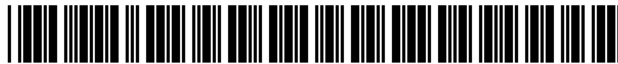

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Friedman et al.

(10) **Patent No.: US 10,424,458 B2**
(45) **Date of Patent: Sep. 24, 2019**

(54) **ELECTRON REFLECTOMETER AND PROCESS FOR PERFORMING SHAPE METROLOGY**

(71) Applicant: **Government of the United States of America, as represented by the Secretary of Commerce**, Gaithersburg, MD (US)

(72) Inventors: **Lawrence H. Friedman**, Silver Spring, MD (US); **Wen-Li Wu**, Gaithersburg, MD (US)

(73) Assignee: **GOVERNMENT OF THE UNITED STATES OF AMERICA, AS REPRESENTED BY THE SECRETARY OF COMMERCE**, Gaithersburg, MD (US)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 0 days.

(21) Appl. No.: **15/980,399**

(22) Filed: **May 15, 2018**

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Related U.S. Application Data

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(51) **Int. Cl.**

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H01J 37/20 (2006.01)
G01B 15/04 (2006.01)
H01J 37/06 (2006.01)
H01J 37/10 (2006.01)
H01J 37/22 (2006.01)

(52) **U.S. Cl.**

CPC ***H01J 37/1471*** (2013.01); ***G01B 15/04*** (2013.01); ***H01J 37/06*** (2013.01); ***H01J 37/10*** (2013.01); ***H01J 37/20*** (2013.01); ***H01J 37/22*** (2013.01); *G01B 2210/56* (2013.01)

(58) **Field of Classification Search**

USPC 250/306, 307, 310

See application file for complete search history.

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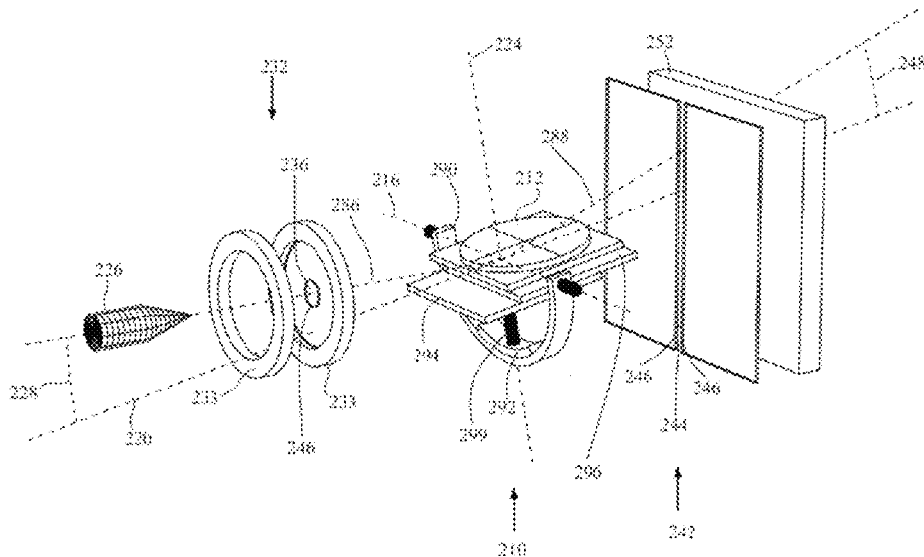
Primary Examiner — Kiet T Nguyen

(74) *Attorney, Agent, or Firm* — Office of Chief Counsel for National Institute of Standards and Technology

(57) **ABSTRACT**

An electron reflectometer includes: a sample stage; a source that produces source electrons; a source collimator; and an electron detector that receives collimated reflected electrons.

17 Claims, 29 Drawing Sheets



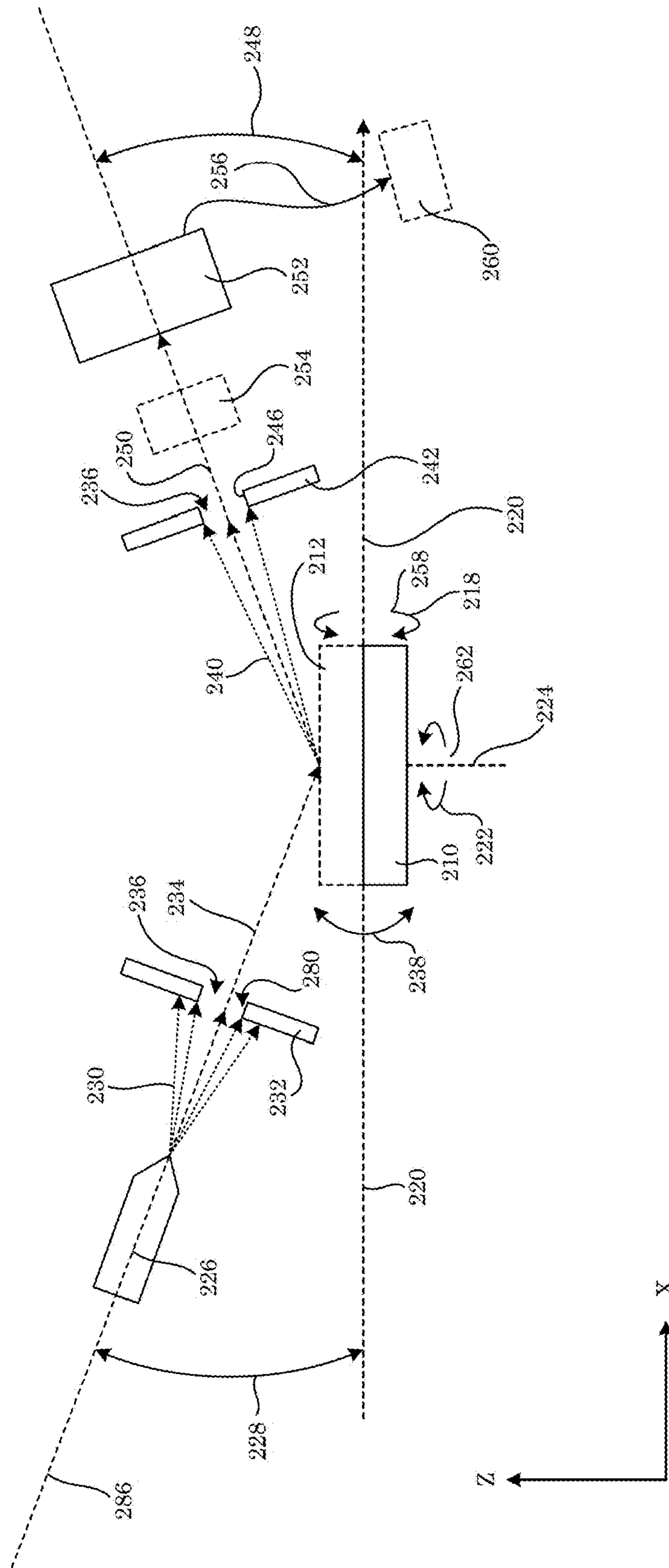


Figure 1

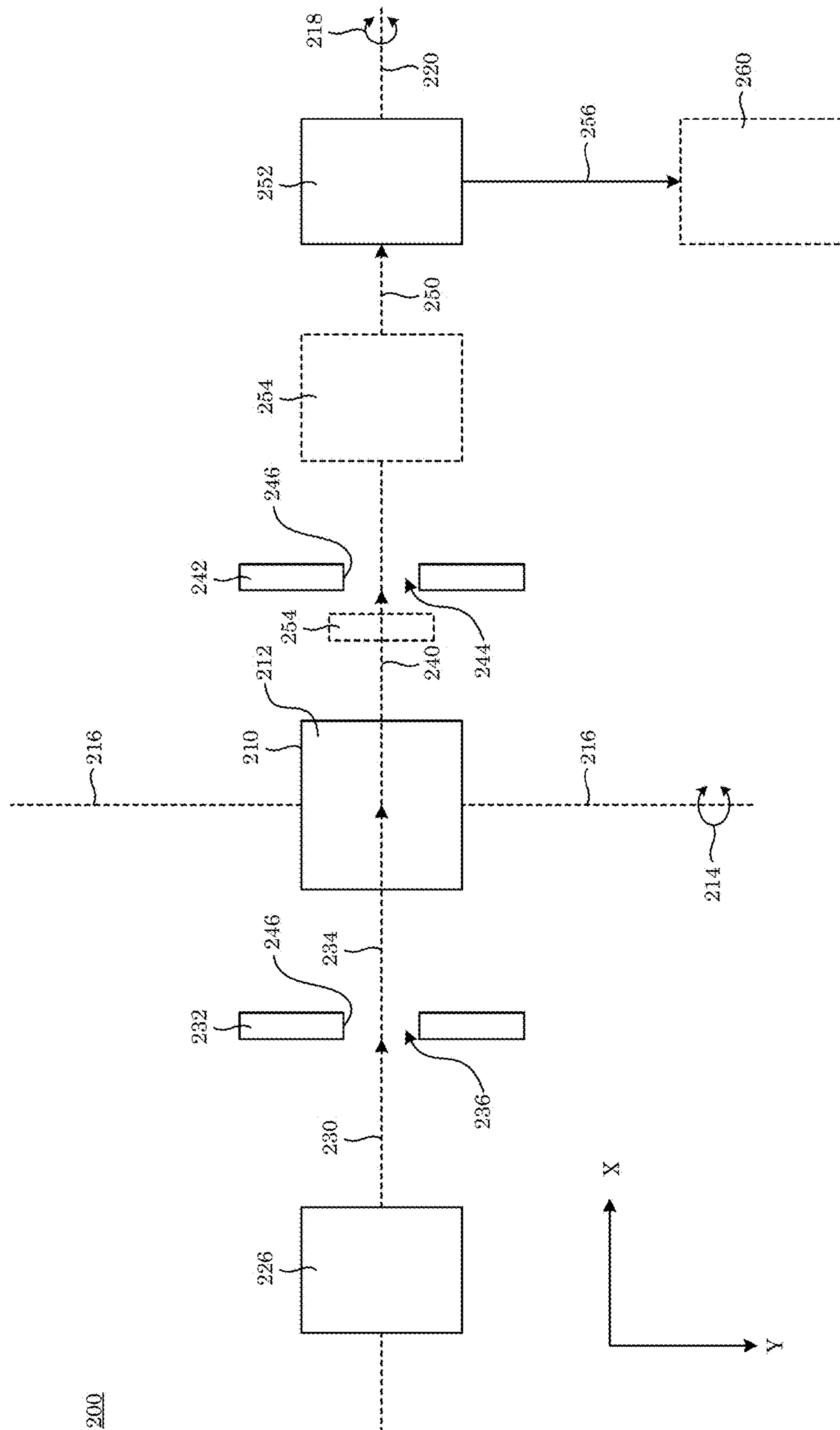


Figure 2

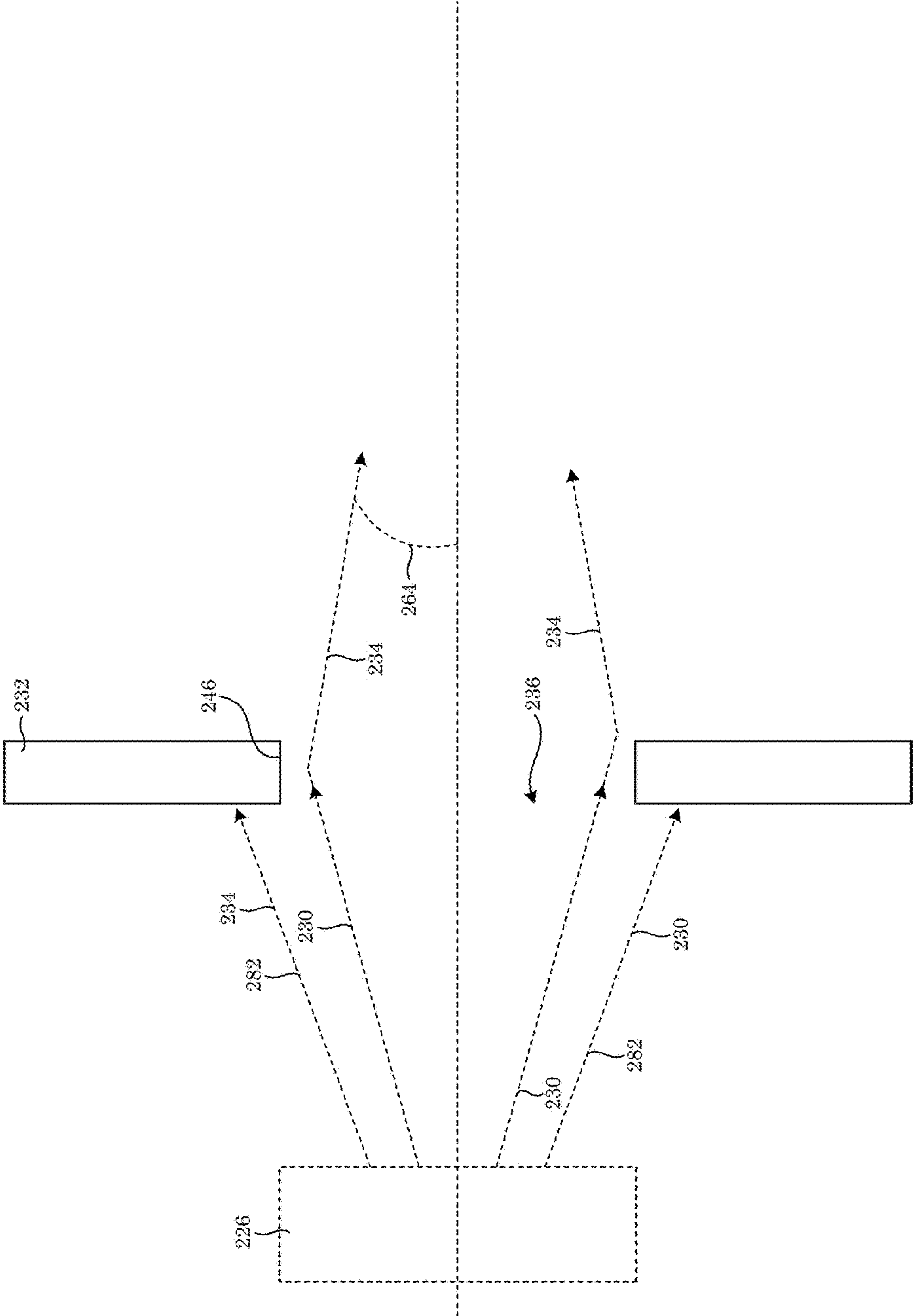
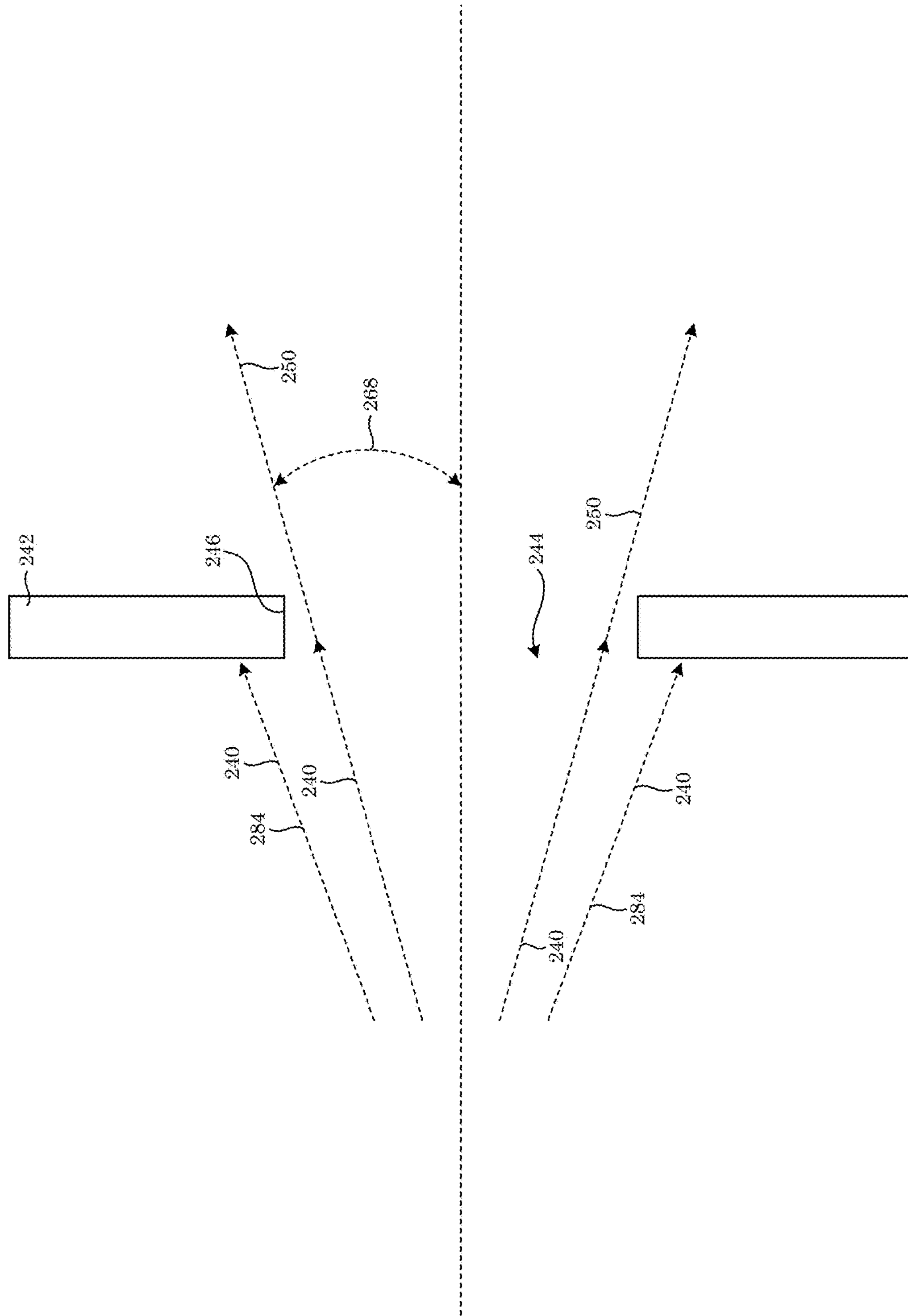


Figure 3



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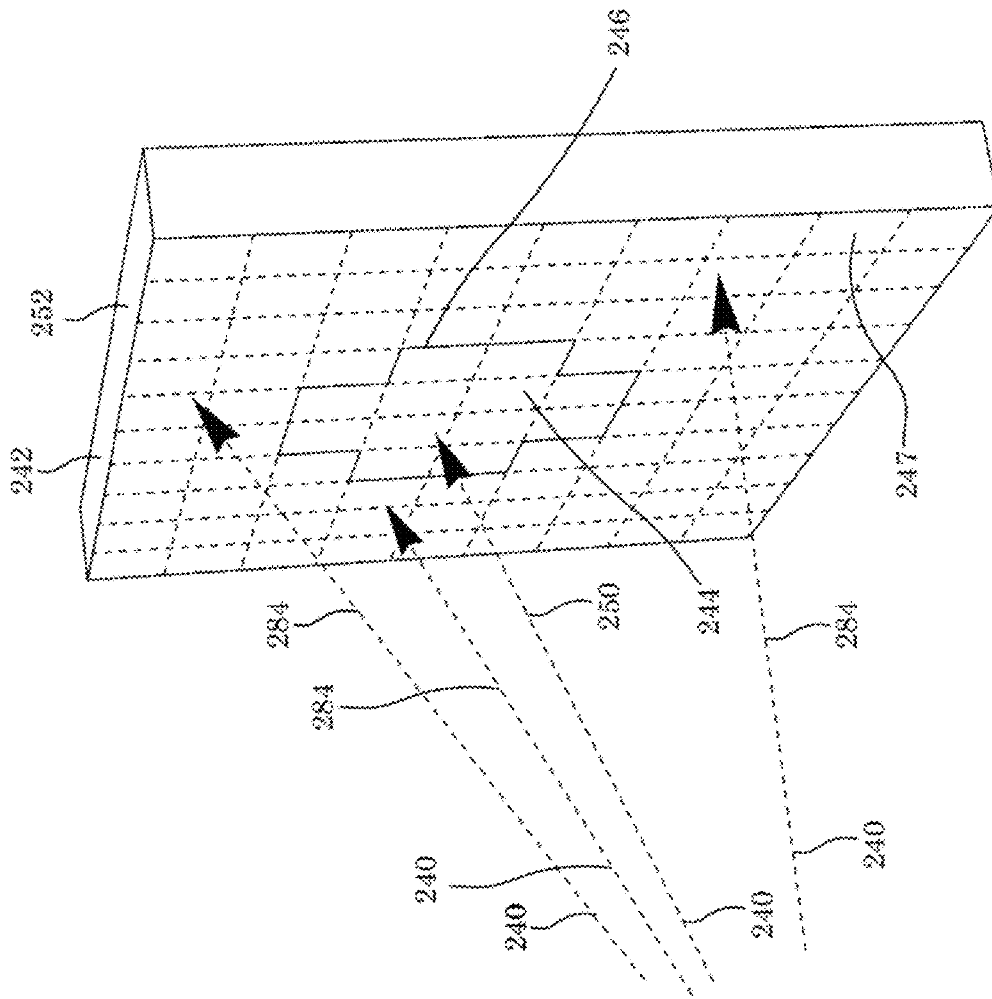
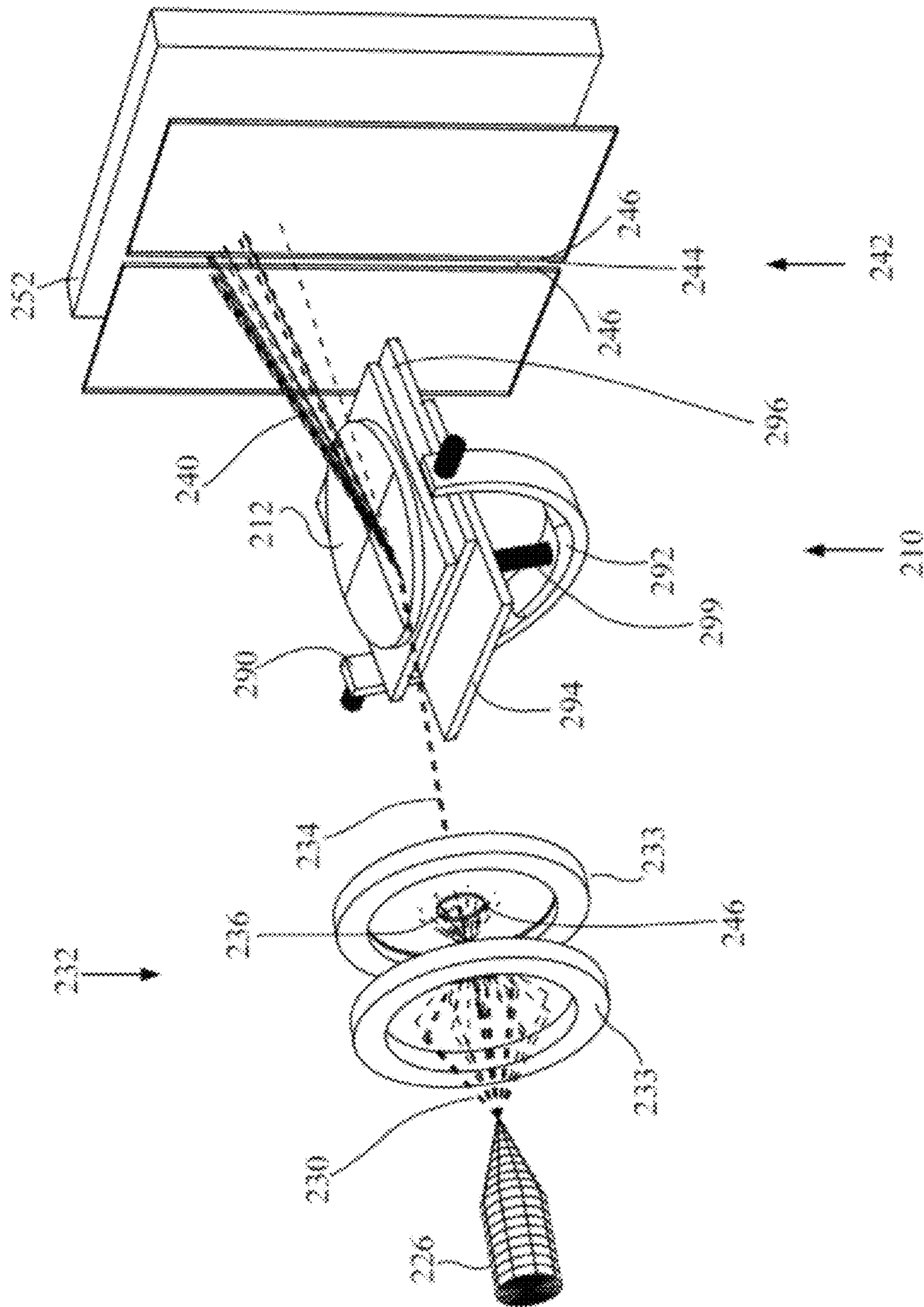


Figure 5

Figure 6



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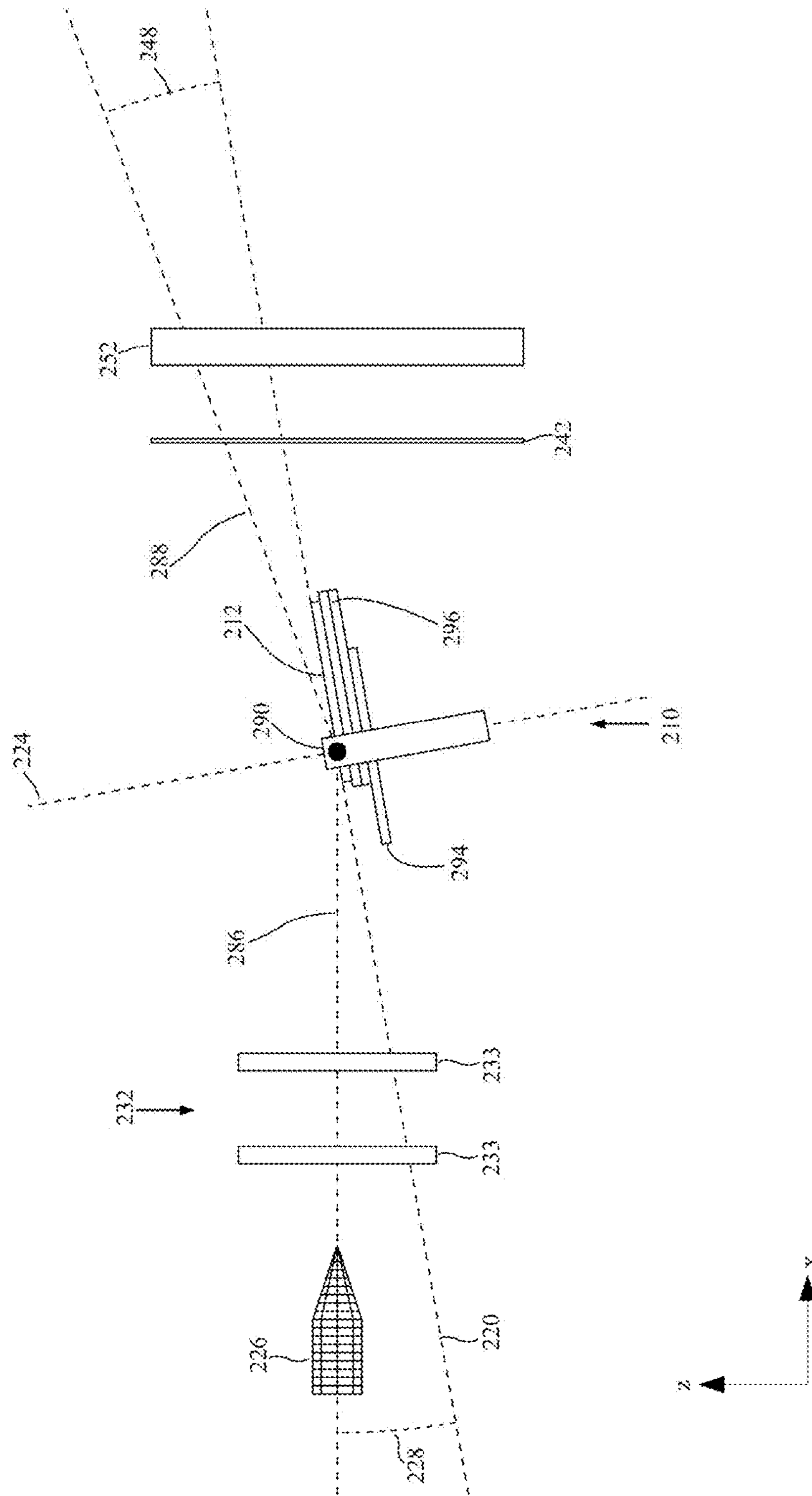

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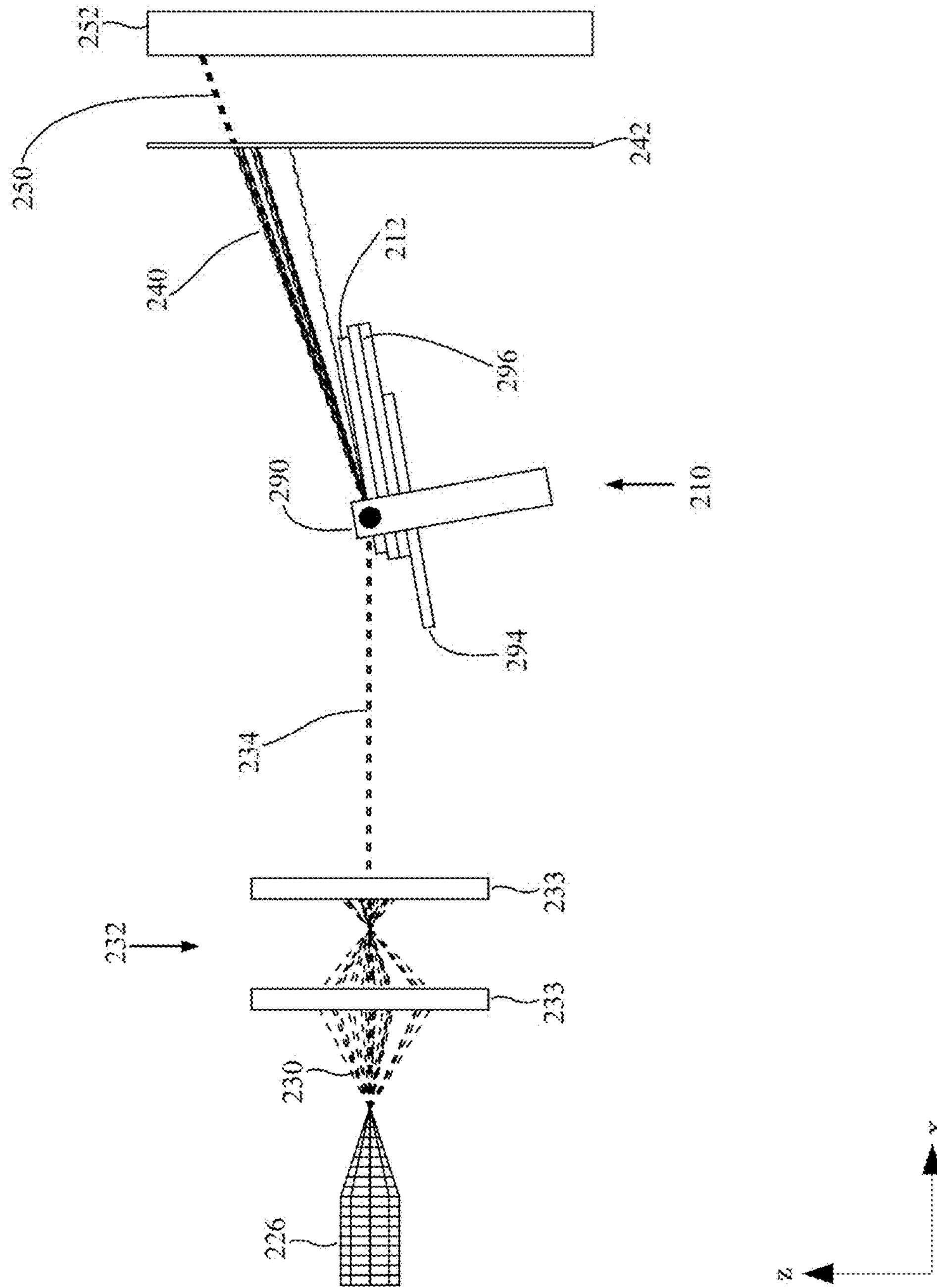

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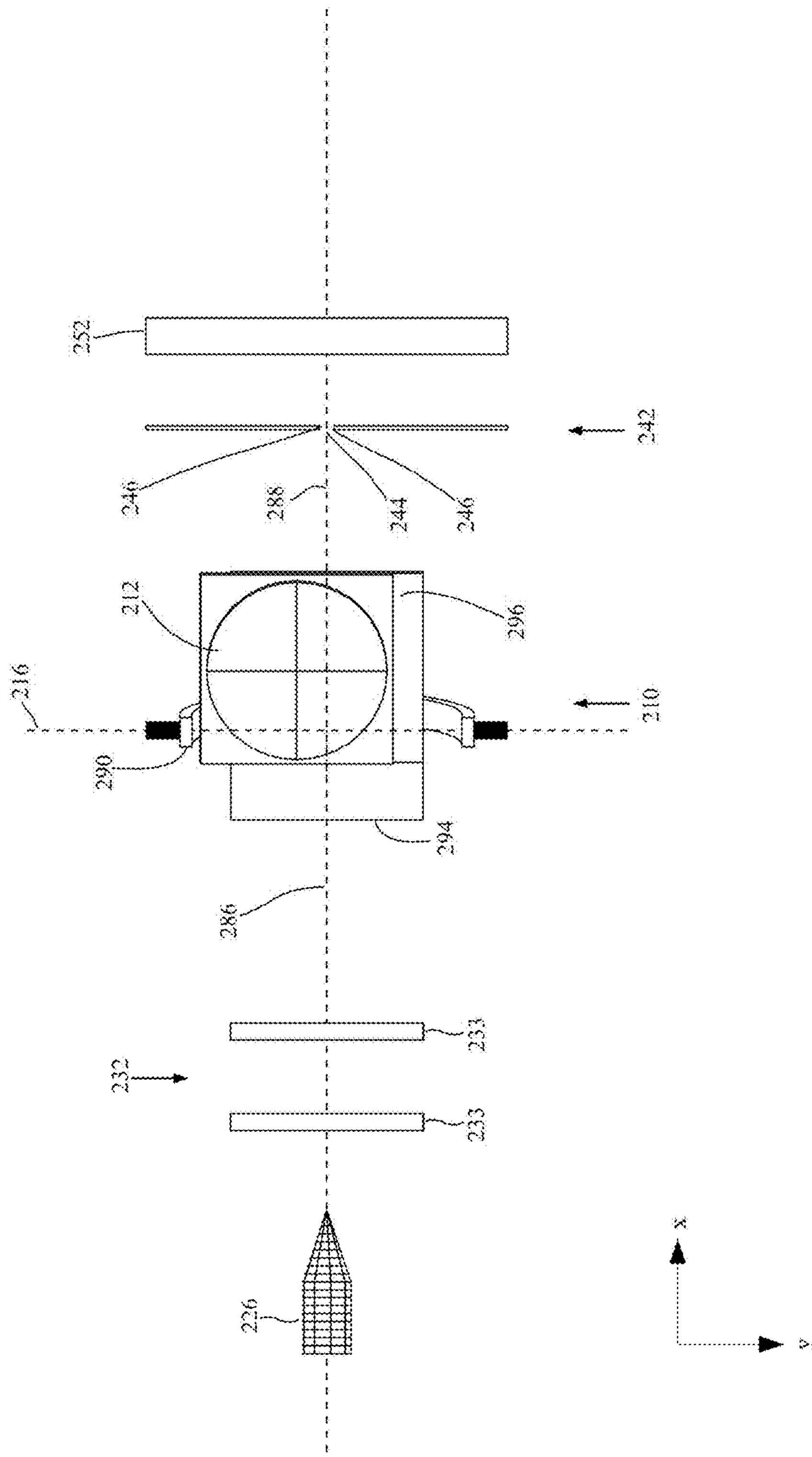

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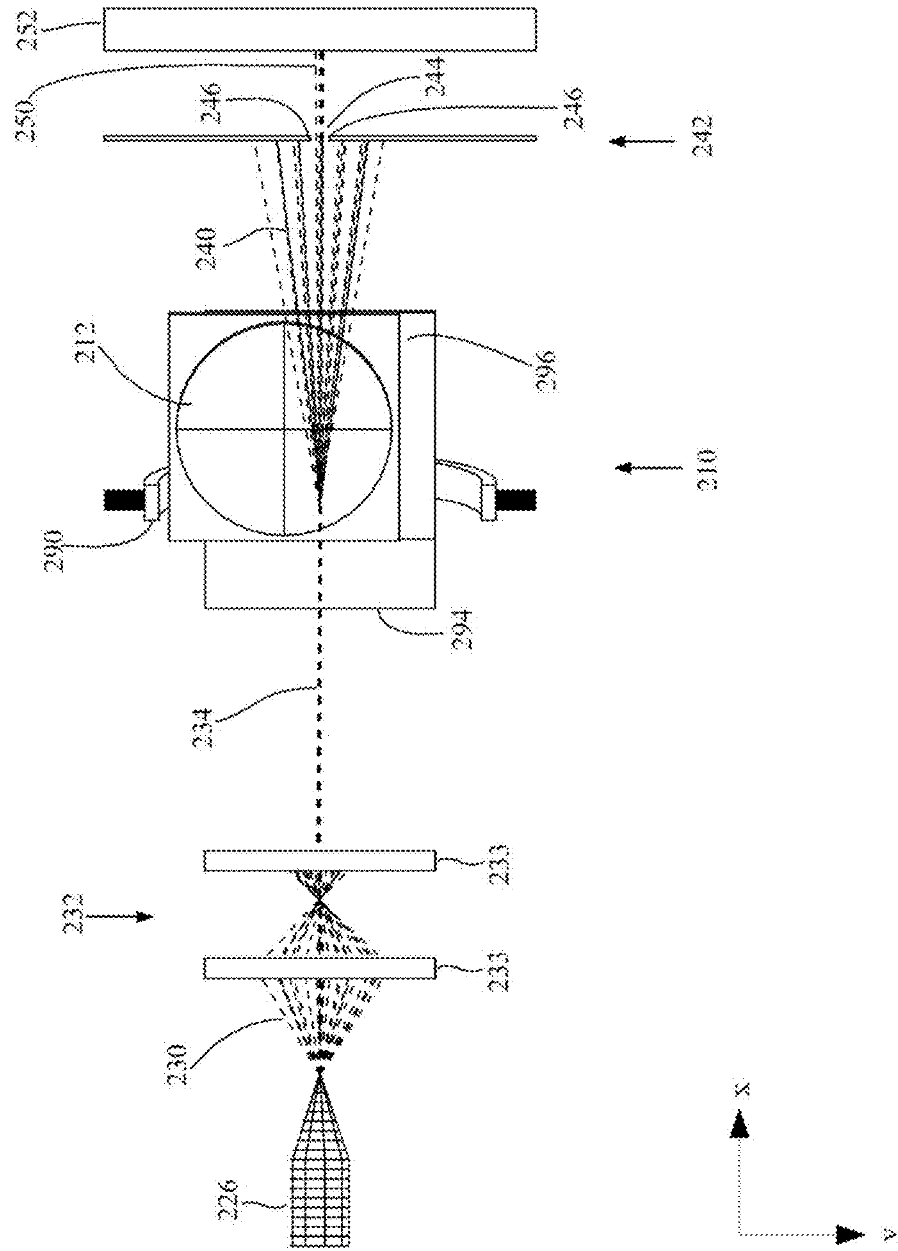

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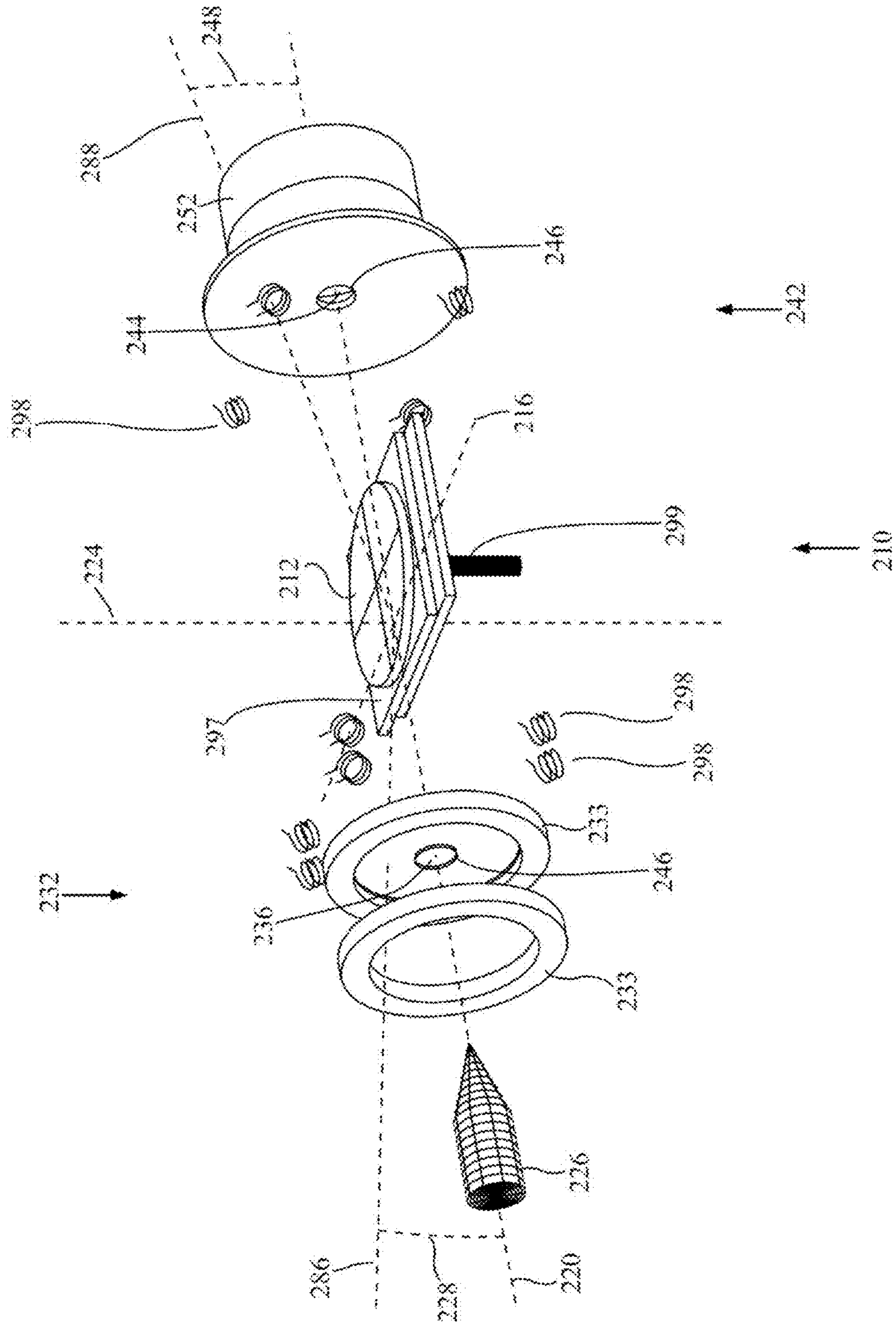

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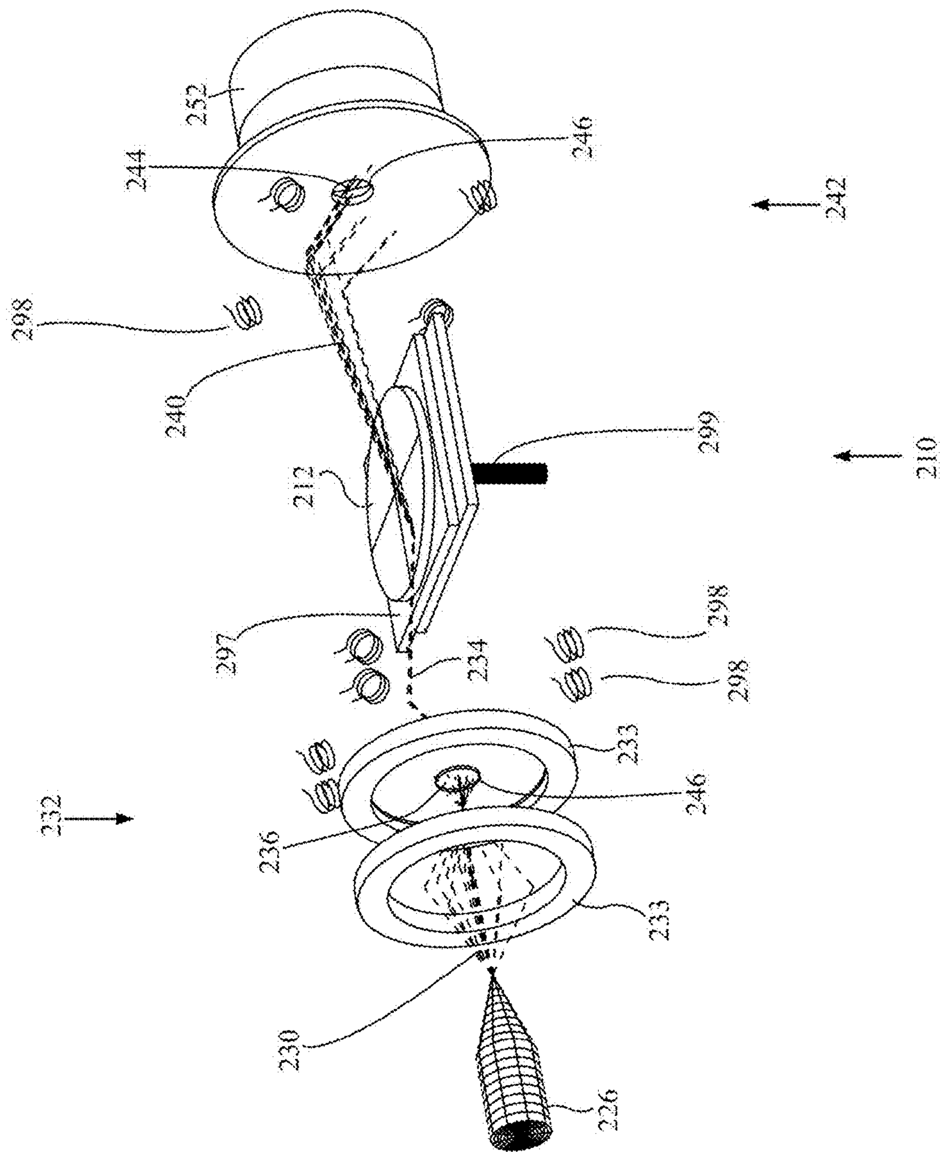

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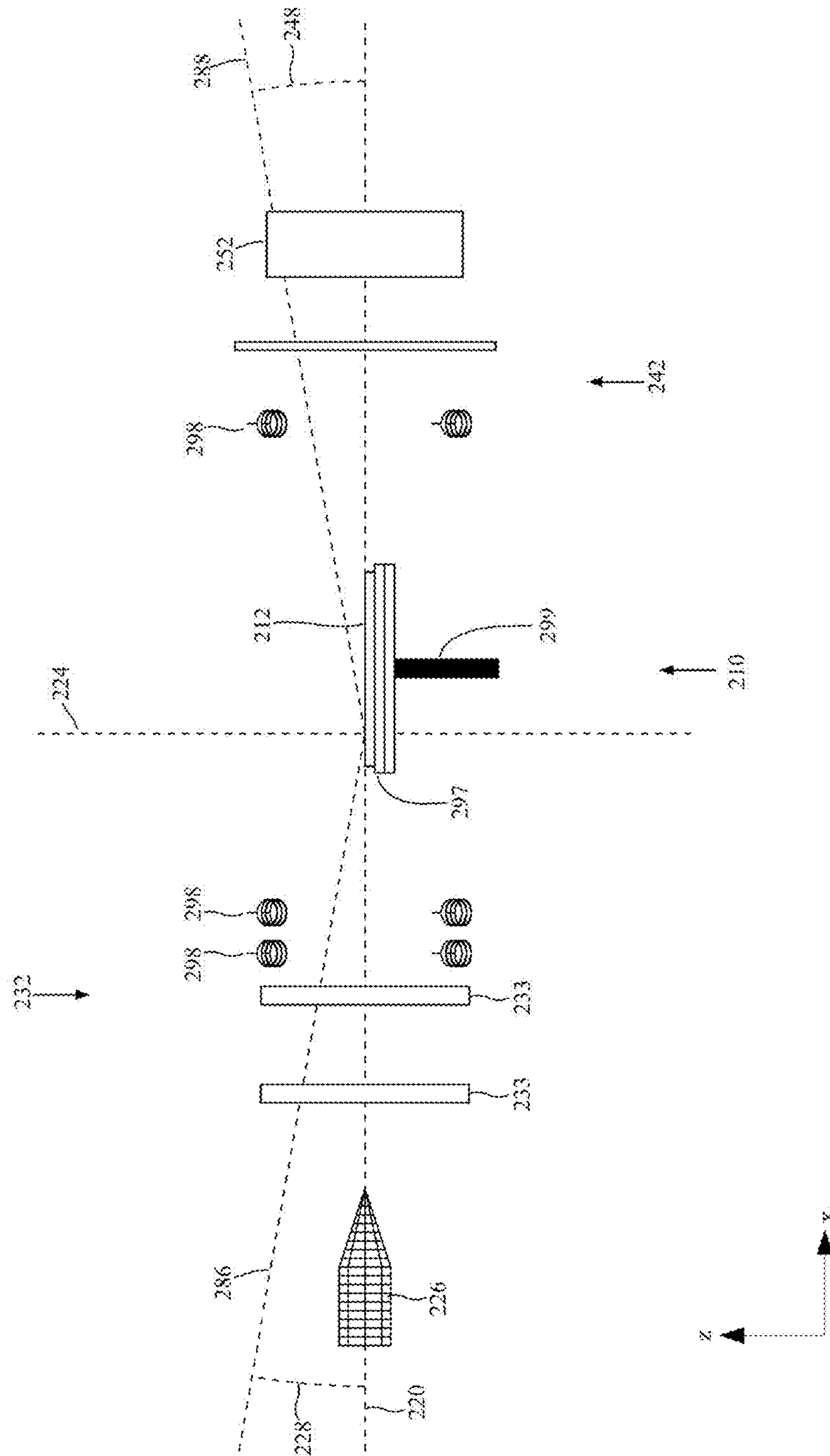
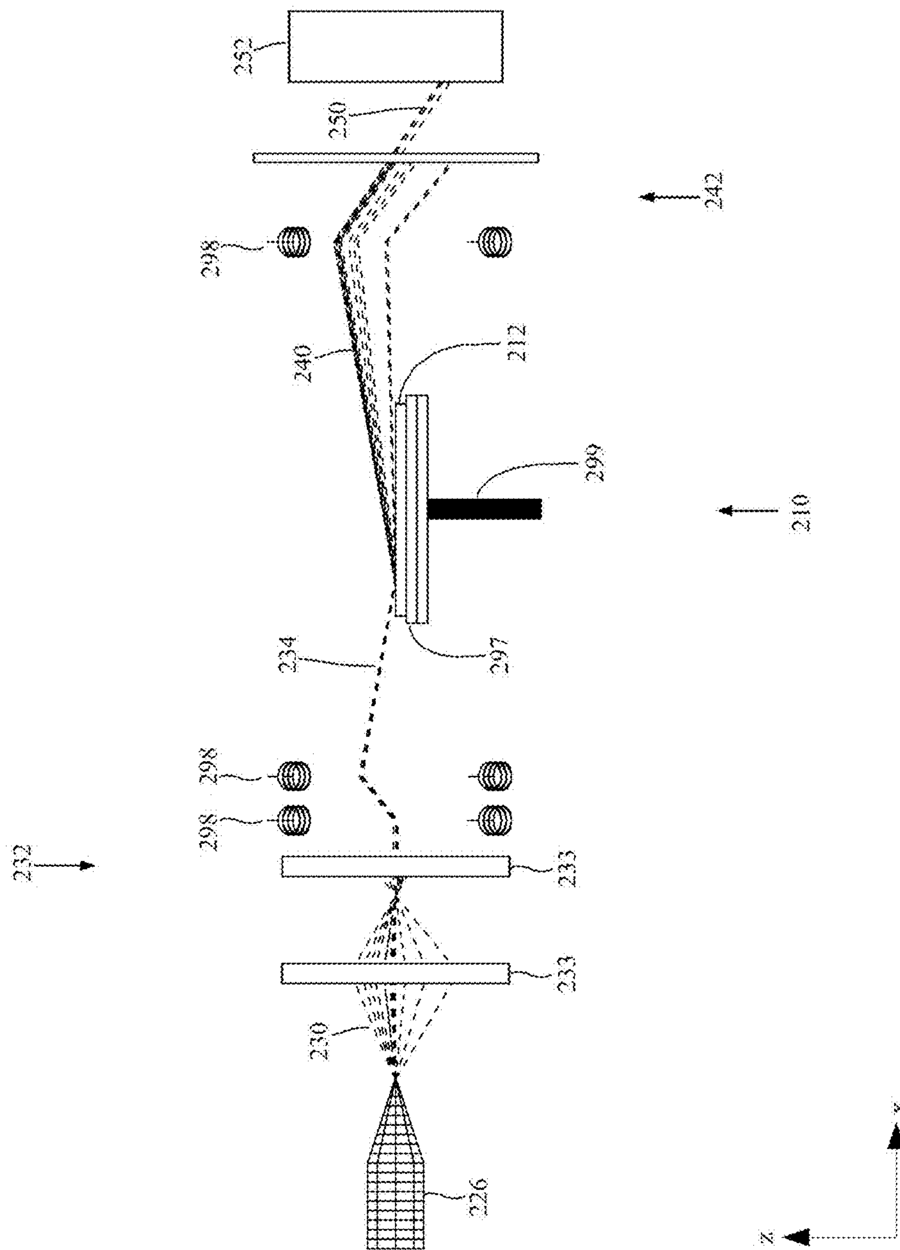


Figure 14



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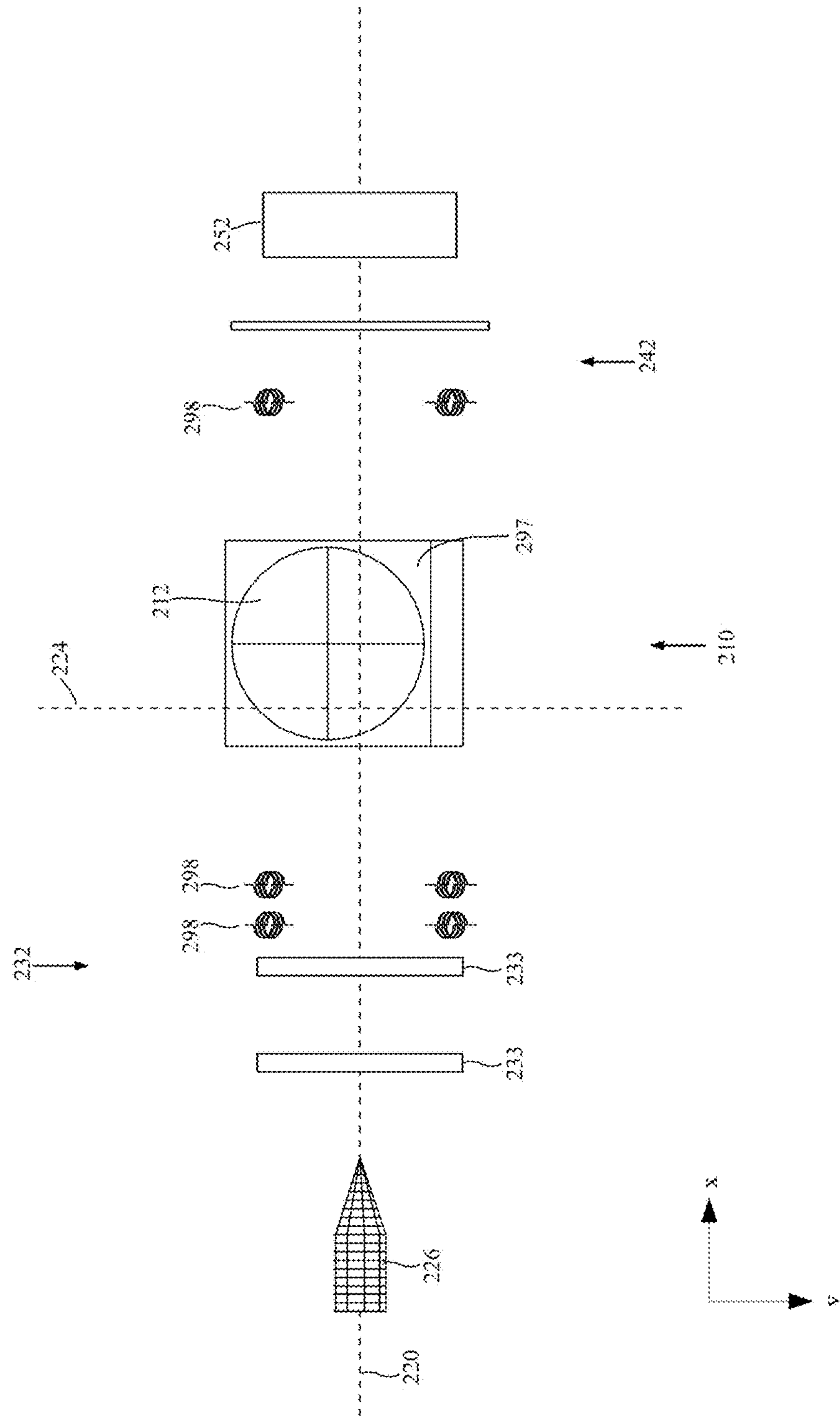

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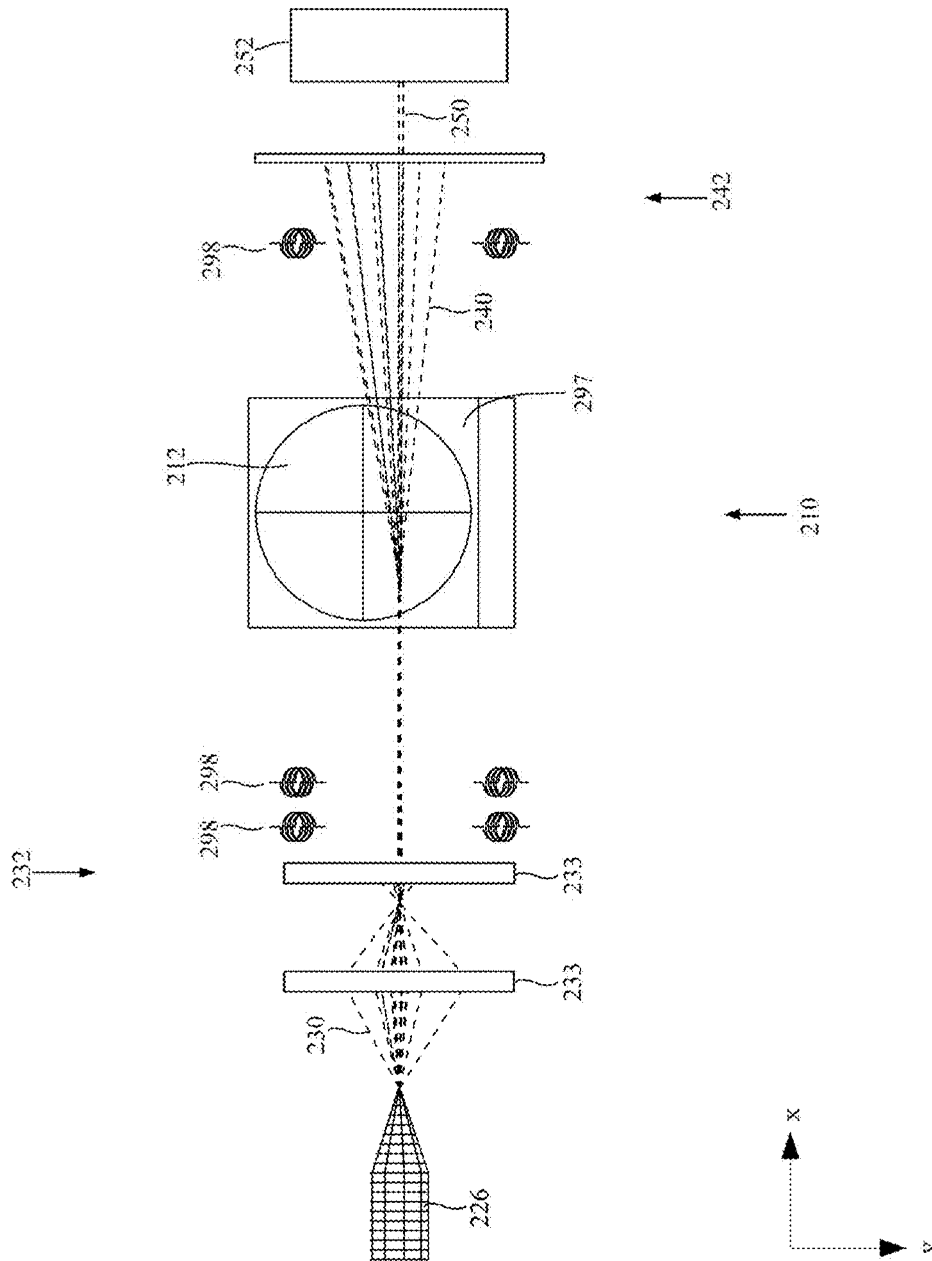

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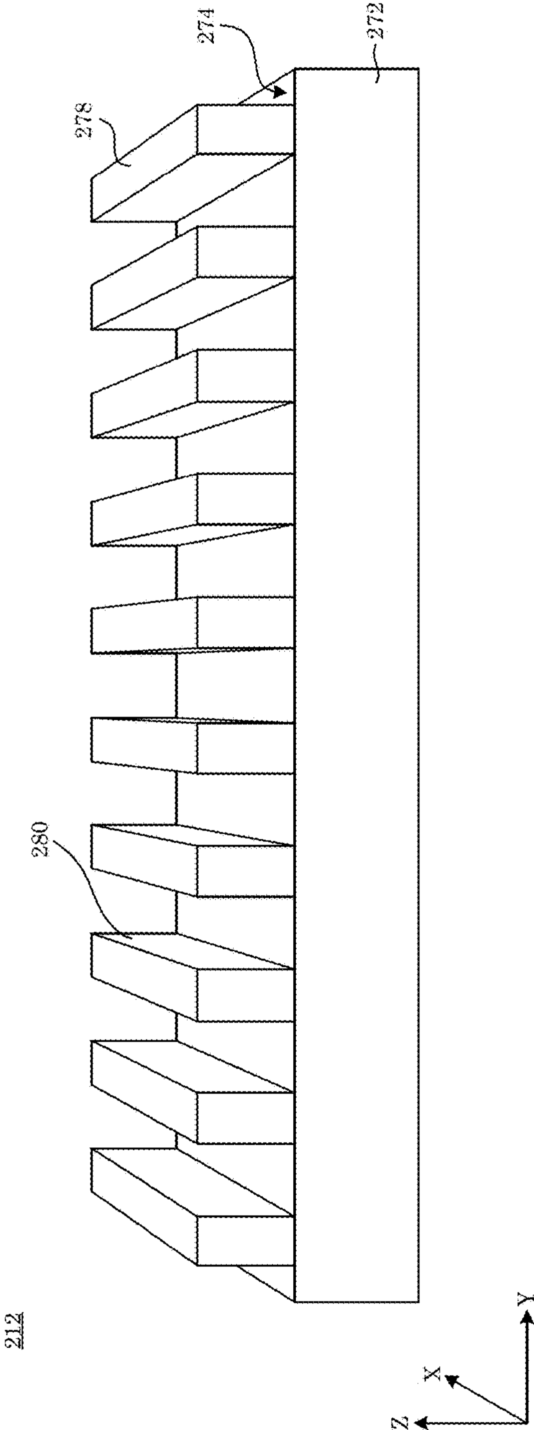

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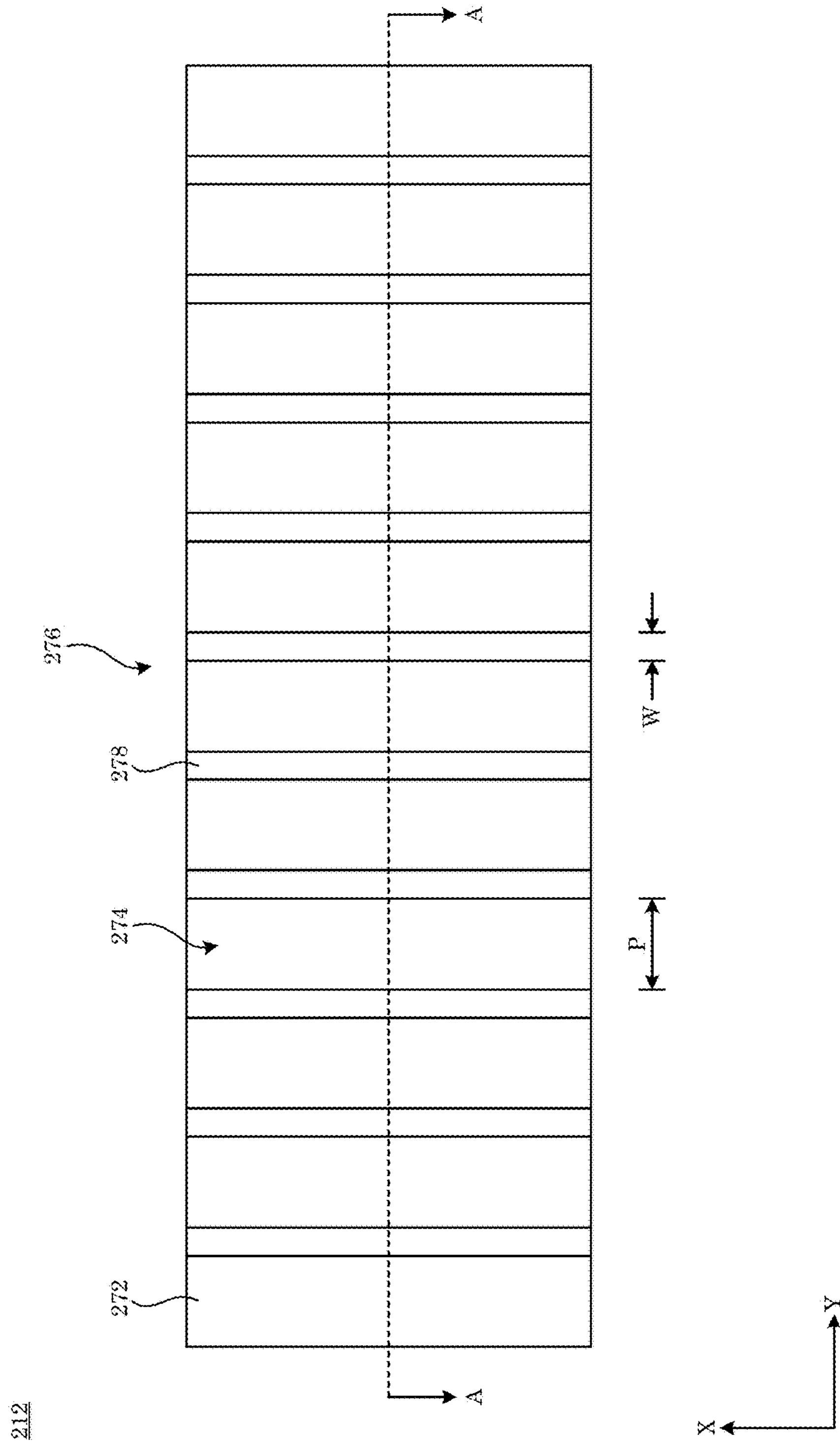

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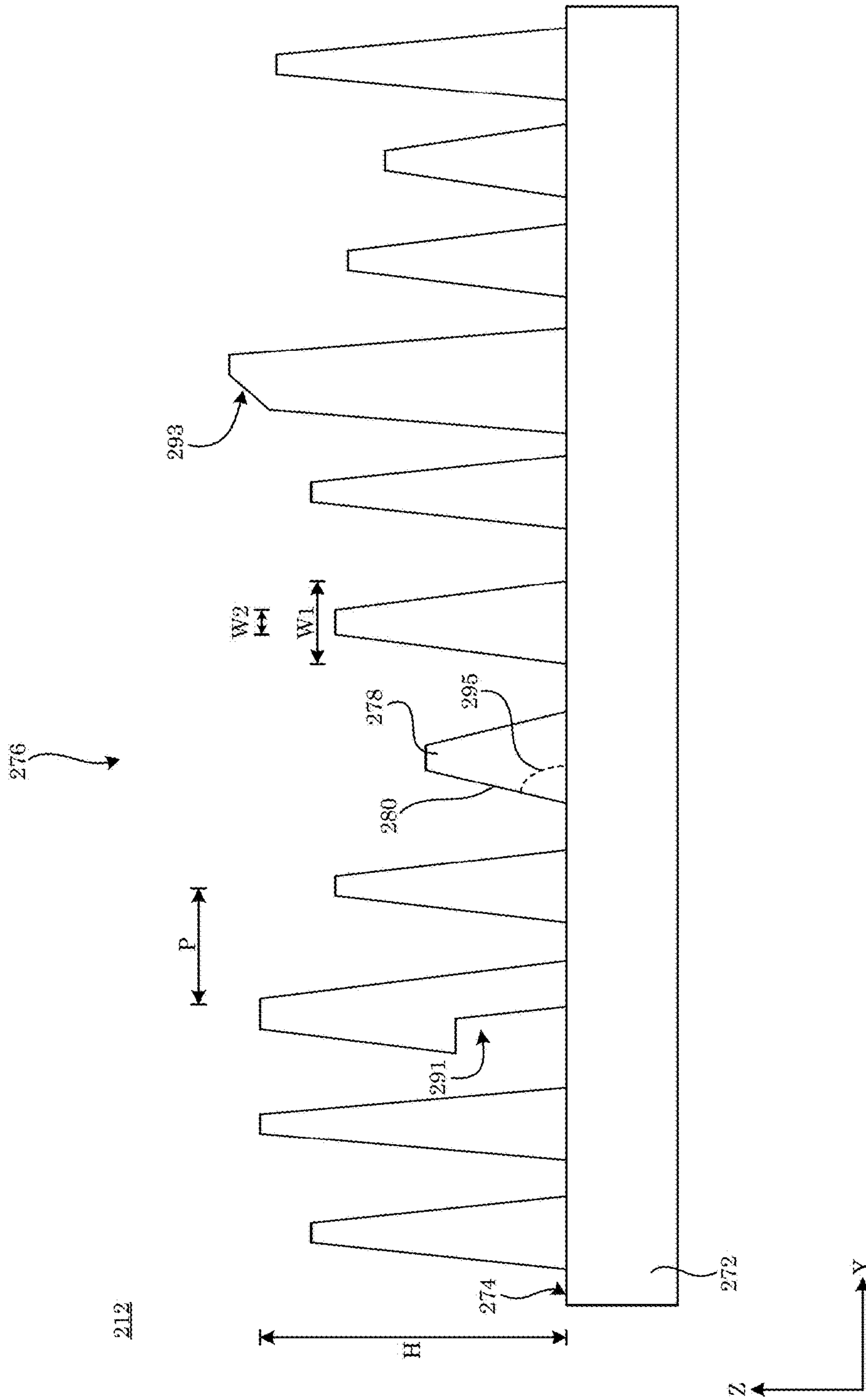


Figure 20

270

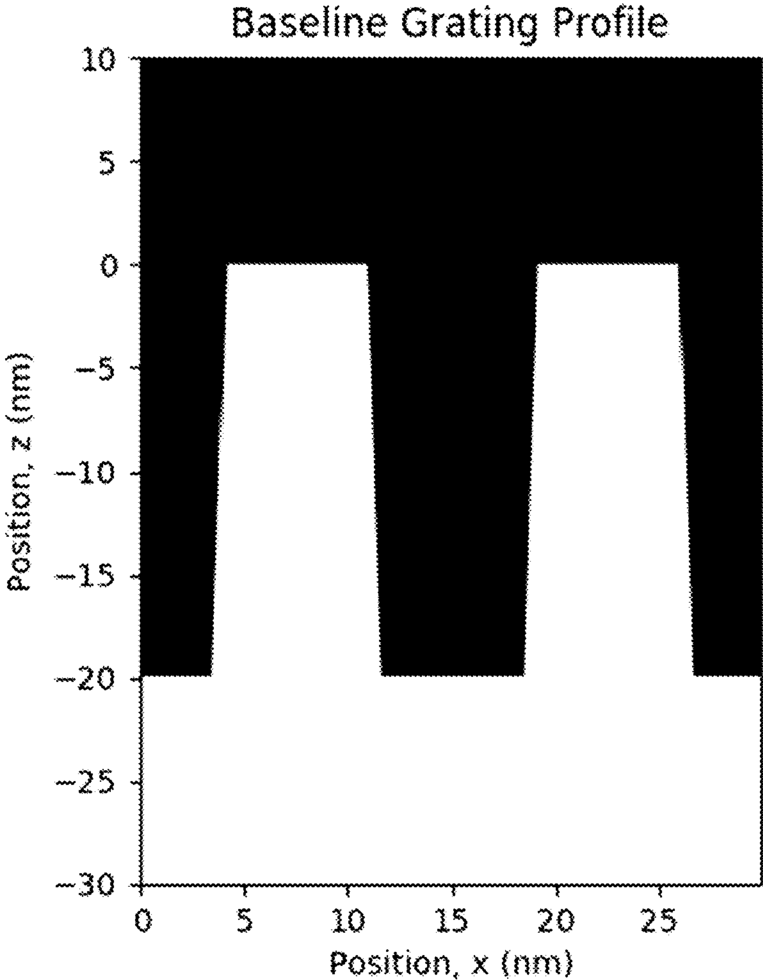
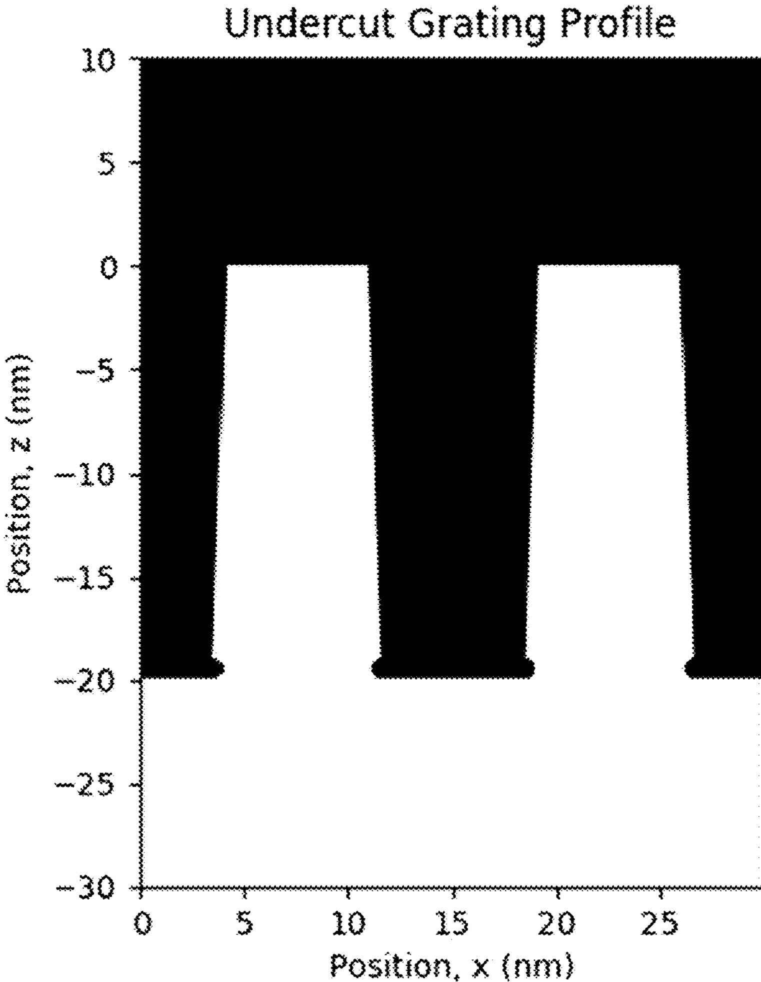


Figure 21

270



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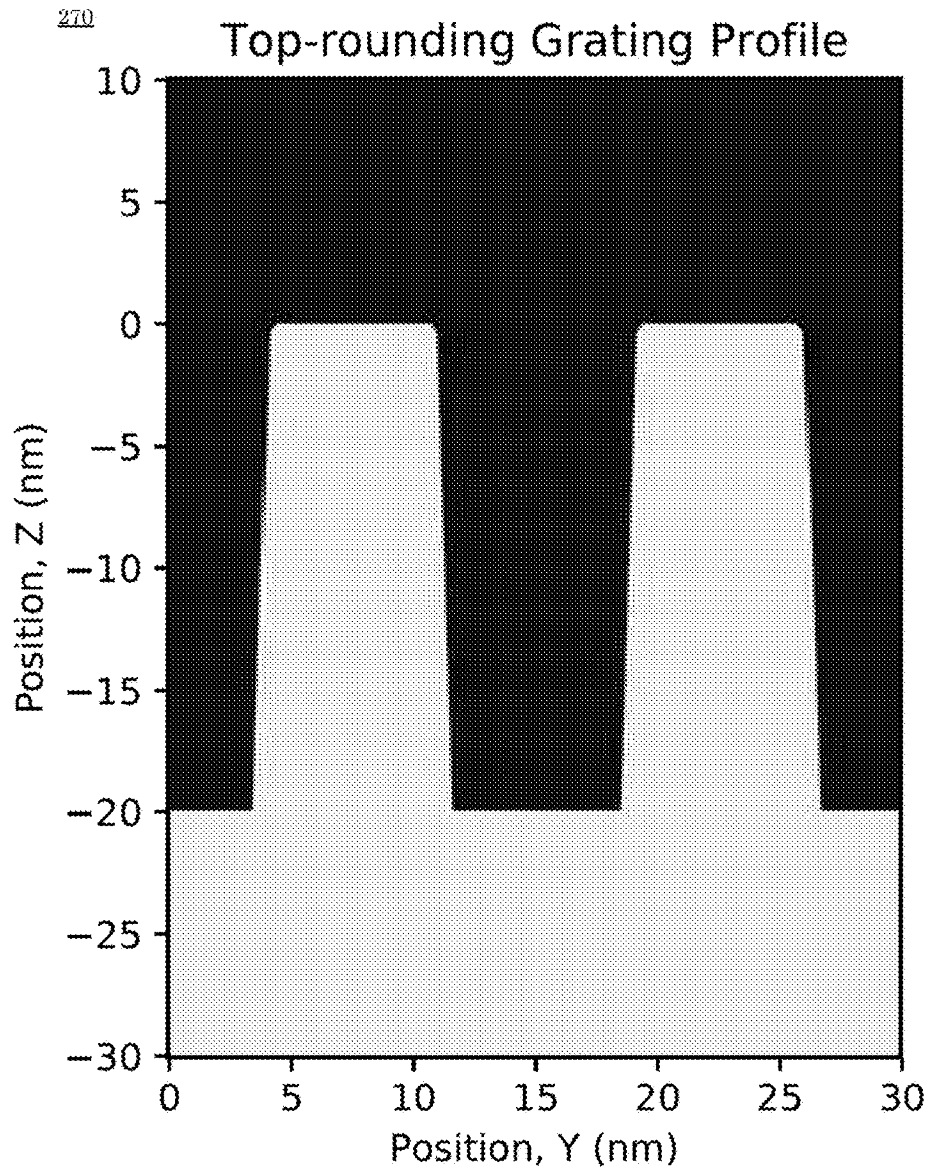
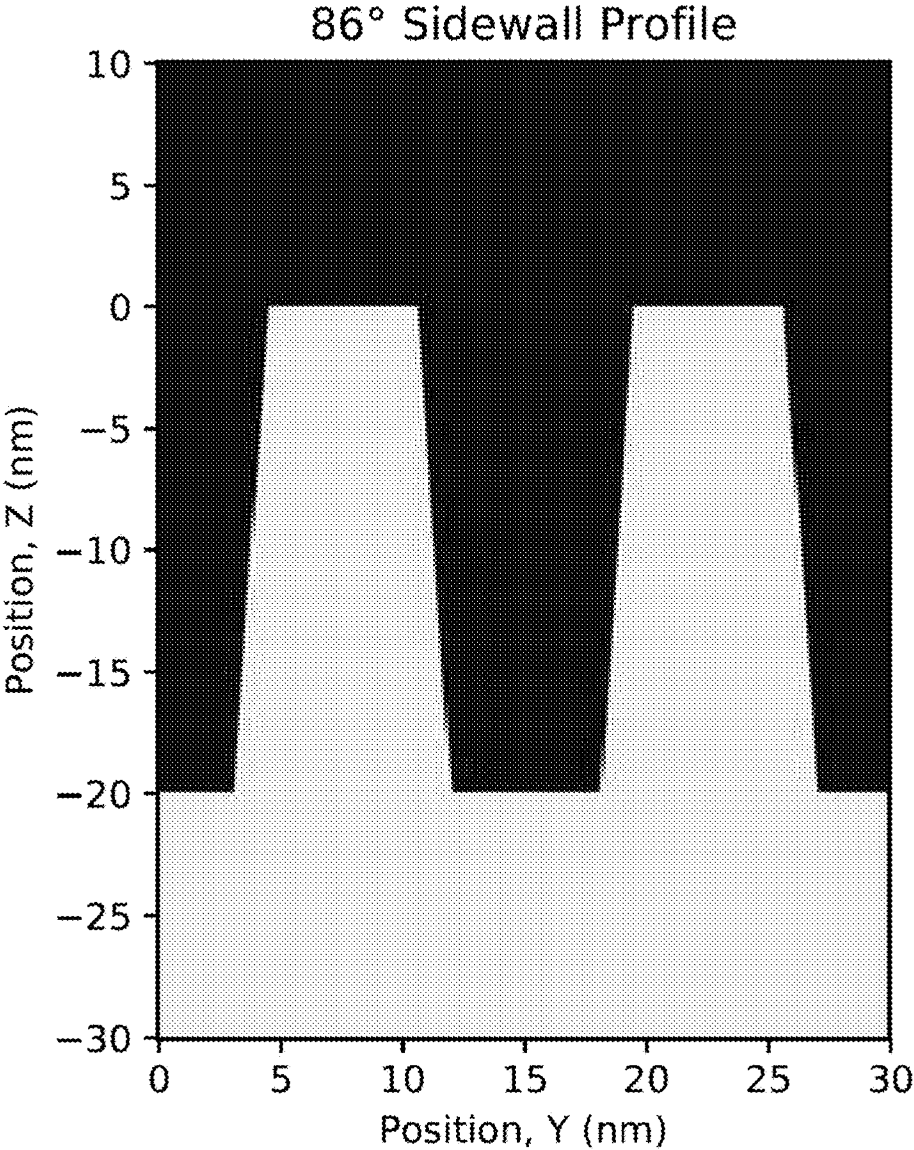


Figure 23

270



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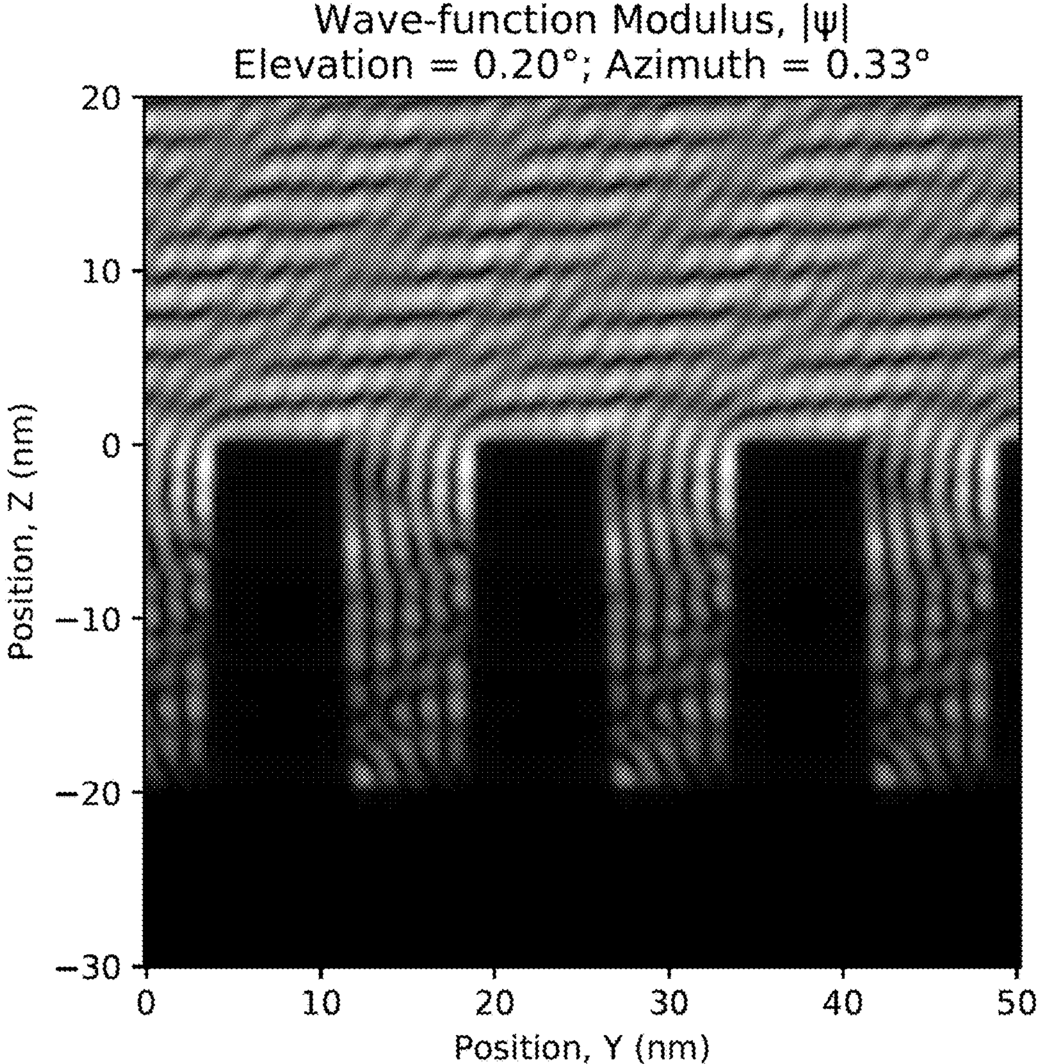

Figure 25

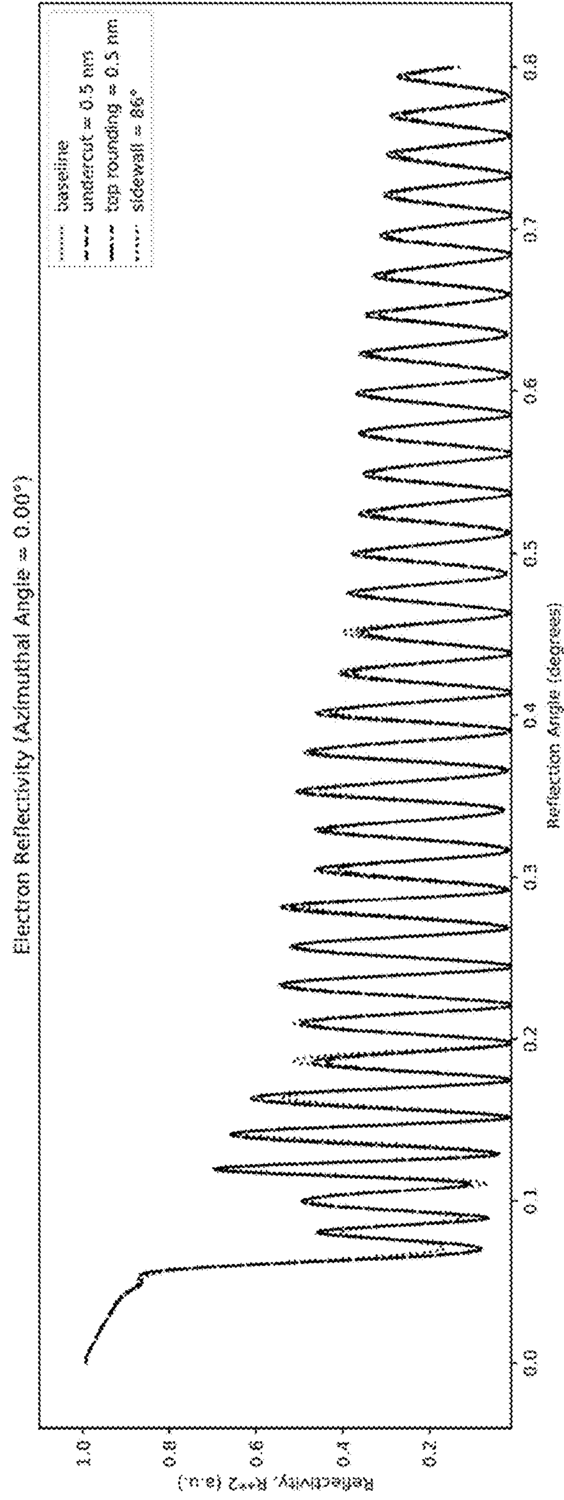

Figure 26

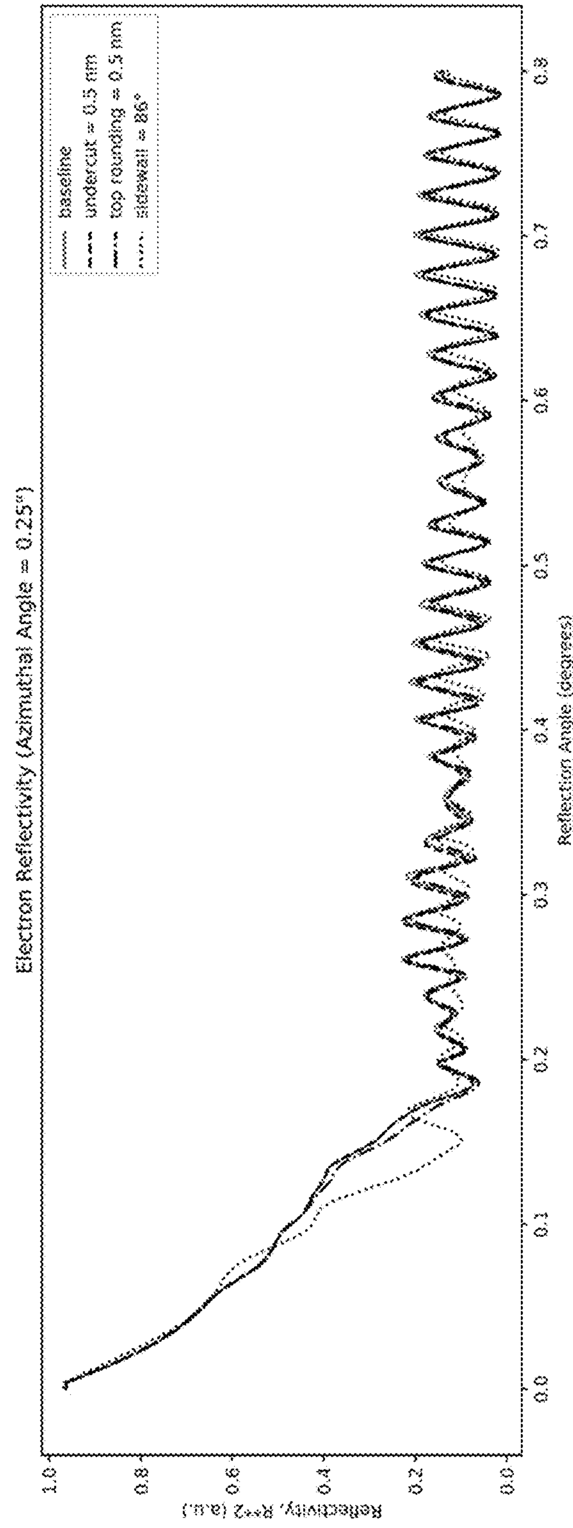

Figure 27

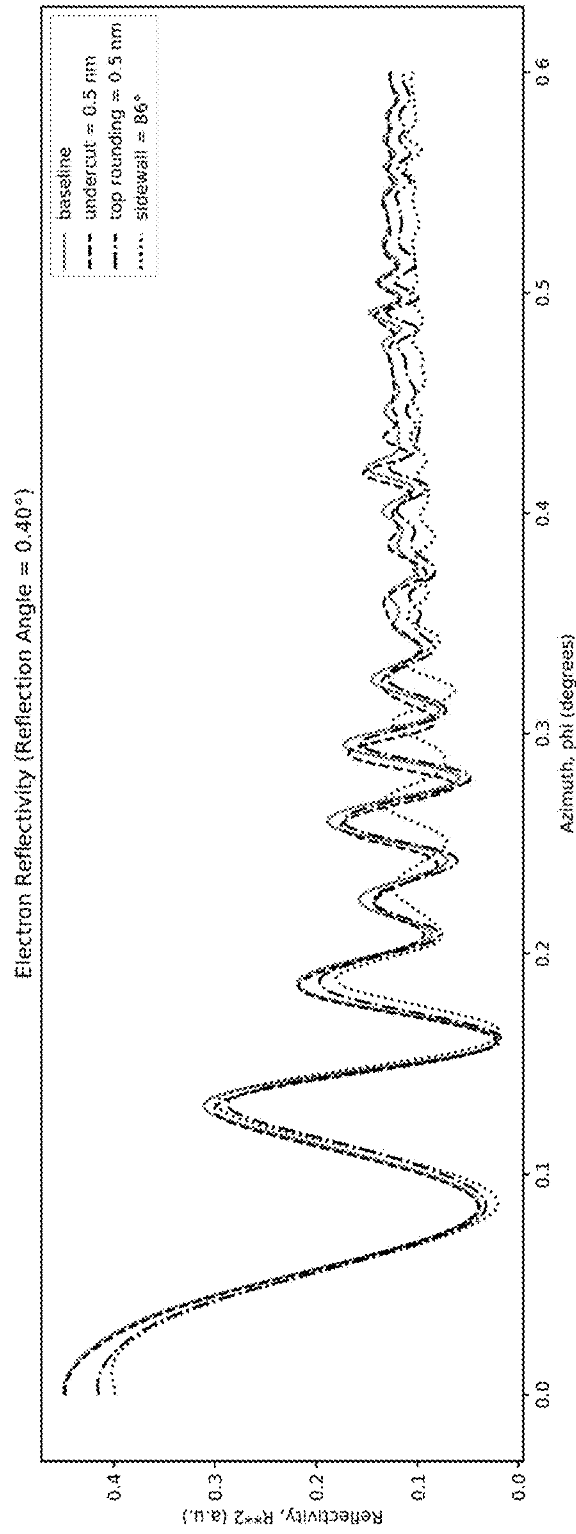

Figure 28

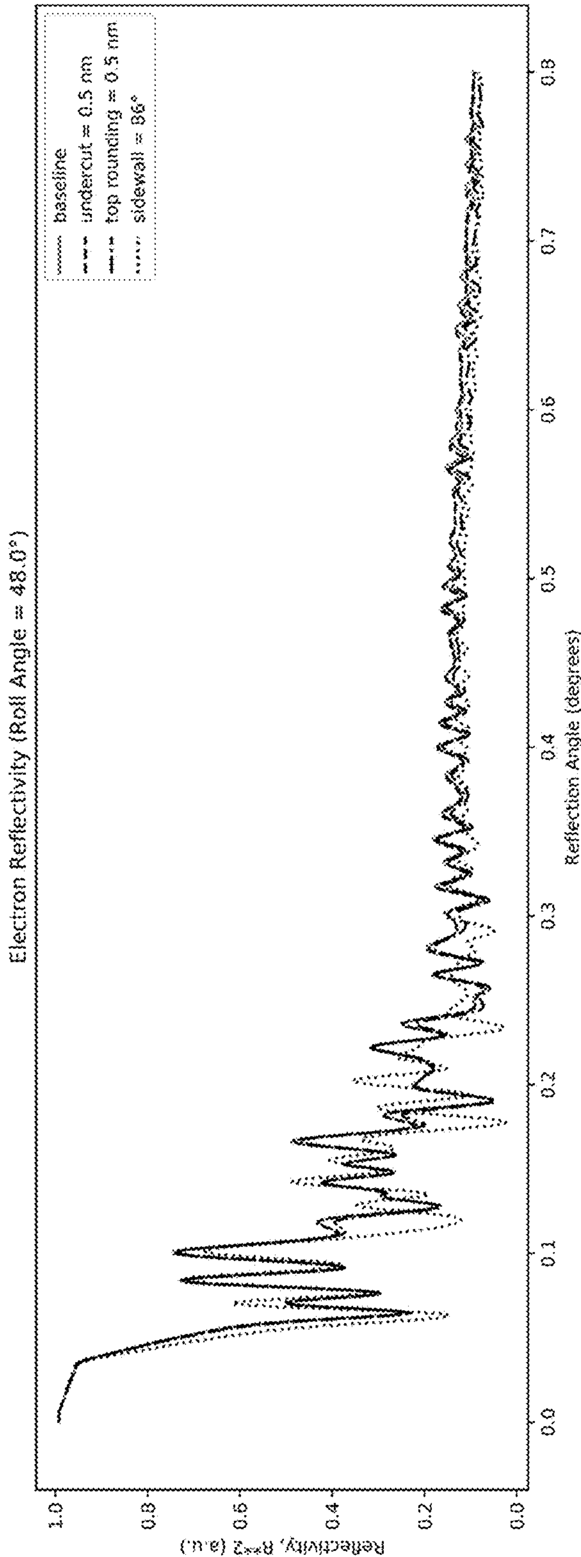

Figure 29

ELECTRON REFLECTOMETER AND PROCESS FOR PERFORMING SHAPE METROLOGY

CROSS REFERENCE TO RELATED APPLICATIONS

This application claims the benefit of U.S. Provisional Patent Application Ser. No. 62/547,937, filed Aug. 21, 2017, the disclosure of which is incorporated herein by reference in its entirety.

STATEMENT REGARDING FEDERALLY SPONSORED RESEARCH

This invention was made with United States Government support from the National Institute of Standards and Technology (NIST), an agency of the United States Department of Commerce. The Government has certain rights in the invention. Licensing inquiries may be directed to the Technology Partnerships Office, NIST, Gaithersburg, Md., 20899; voice (301) 301-975-2573; email tpo@nist.gov; reference NIST Ser. No. 17-980,399.

BRIEF DESCRIPTION

Disclosed is an electron reflectometer comprising: a sample stage that: receives a sample comprising a sample surface; disposes the sample in a position to be analyzed; moves the sample surface to be positioned perpendicular to an azimuthal axis and coincident at a point of common intersection of a pitch axis pseudo-periodic, roll axis pseudo-periodic, and azimuthal axis pseudo-periodic; provides a pitch rotation pseudo-periodic through a pitch angle pseudo-periodic to the sample about a pitch axis pseudo-periodic; provides a roll rotation pseudo-periodic through a roll angle pseudo-periodic to the sample about a roll axis pseudo-periodic, the pitch axis pseudo-periodic being perpendicular to and independent of the roll axis; and provides an azimuthal rotation pseudo-periodic through an azimuthal angle pseudo-periodic to the sample about an azimuthal axis pseudo-periodic, such that the sample can be rotated into a measurement position; a source pseudo-periodic moveably disposed at an incident angle pseudo-periodic with respect to the sample stage pseudo-periodic and that produces source electrons pseudo-periodic directed toward the sample; a source collimator pseudo-periodic interposed between the source and the sample stage pseudo-periodic sample pseudo-periodic and that: receives the source electrons pseudo-periodic; collimates the source electrons pseudo-periodic; and produces incident electrons pseudo-periodic from the source electrons pseudo-periodic in response to collimating the source electrons pseudo-periodic, the source collimator comprising an electron lens pseudo-periodic and source transmission aperture pseudo-periodic having an incident angular width pseudo-periodic from 0.pseudo-periodic° to 5° and that provides incident electrons pseudo-periodic along an incident direction pseudo-periodic at incident angle pseudo-periodic providing an incident footprint pseudo-periodic of impinging electrons on sample surface pseudo-periodic at the point of common intersection with pitch axis pseudo-periodic, roll axis pseudo-periodic and azimuthal axis pseudo-periodic, with incident angle pseudo-periodic being adjustable from 0° to 5° relative to the plane through the pitch axis pseudo-periodic and the roll axis and incident footprint having length and width controllable via source collimator; a detection collimator pseudo-periodic disposed at a detection angle pseudo-periodic with respect to the sample stage pseudo-periodic and that: receives reflected electrons pseudo-periodic that are reflected by the sample and produced from the incident electrons pseudo-periodic; collimates the reflected electrons pseudo-periodic; and produces collimated reflected electrons pseudo-periodic from the reflected electrons pseudo-periodic in response to collimating the reflected electrons pseudo-periodic, the detection collimator pseudo-periodic comprising a detection transmission aperture pseudo-periodic having a detection angular width pseudo-periodic from 0.pseudo-periodic° to 5°, and the detection angle being adjustable from 0° to 5° relative to a plane through the pitch axis pseudo-periodic and the roll axis; and an electron detector pseudo-periodic that receives the collimated reflected electrons pseudo-periodic, the electron detector pseudo-periodic being disposed at the detection angle and with the detection collimator pseudo-periodic interposed between the sample stage pseudo-periodic and the electron detector pseudo-periodic.

Also disclosed is a process for performing shape metrology of a sample pseudo-periodic, the process comprising: producing the source electrons pseudo-periodic; receiving, by the source collimator, the source electrons from the source; collimating, by the source collimator, the source electrons; producing, by the source collimator, the incident electrons pseudo-periodic from the source electrons; subjecting the sample disposed on the sample stage pseudo-periodic to the incident electrons pseudo-periodic from the source collimator with electrons impinging upon the sample surface pseudo-periodic within an incident footprint pseudo-periodic that has length and width controllable by source collimator pseudo-periodic; producing reflected electrons pseudo-periodic from the incident electrons pseudo-periodic in response to receipt of the incident electrons pseudo-periodic by the sample; collimating, by the detection collimator pseudo-periodic, the reflected electrons pseudo-periodic; producing, by the detection collimator pseudo-periodic, the collimated reflected electrons pseudo-periodic; and receiving, by the electron detector, the collimated reflected electrons pseudo-periodic from the detection collimator pseudo-periodic to perform shape metrology of the sample.

BRIEF DESCRIPTION OF THE DRAWINGS

The following descriptions should not be considered limiting in any way. With reference to the accompanying drawings, like elements are numbered alike.

FIG. **1** shows a side view in a x-z plane of electron reflectometer;

FIG. **2** shows a top view in an x-y plane of the electron reflectometer shown in FIG. **1**;

FIG. **3** shows collimation of source electrons pseudo-periodic;

FIG. **4** shows collimation of reflected electrons pseudo-periodic;

FIG. **5** shows virtual collimation and detection of reflected electrons pseudo-periodic;

FIG. **6** shows oblique view of embodiment of electron reflectometer pseudo-periodic with rotation axes and electron directions shown;

FIG. **7** shows oblique view of embodiment of electron reflectometer pseudo-periodic with electrons shown;

FIG. **8** shows side view in x-z plane of embodiment of electron reflectometer pseudo-periodic with rotation axes and electron directions shown.

FIG. **9** shows side view in x-z plane embodiment of electron reflectometer pseudo-periodic with electrons shown;

FIG. **10** shows top view in x-y plane of embodiment of electron reflectometer pseudo-periodic with rotation axes and electron directions shown.

FIG. **11** shows top view in x-y plane of embodiment of electron reflectometer pseudo-periodic with electrons shown;

FIG. **12** shows oblique view of embodiment of electron reflectometer pseudo-periodic with rotation axes and electron directions shown;

FIG. **13** shows oblique view of embodiment of electron reflectometer pseudo-periodic with electrons shown;

FIG. **14** shows side view in x-z plane of embodiment of electron reflectometer pseudo-periodic with rotation axes and electron directions shown.

FIG. **15** shows side view in x-z plane embodiment of electron reflectometer pseudo-periodic with electrons shown;

FIG. **16** shows top view in x-y plane of embodiment of electron reflectometer pseudo-periodic with rotation axes and electron directions shown.

FIG. **17** shows top view in x-y plane of embodiment of electron reflectometer pseudo-periodic with electrons shown;

FIG. **18** shows a perspective view of a sample pseudo-periodic;

FIG. **19** shows a top view in X-Y plane of the sample shown in FIG. **18**;

FIG. **20** shows a cross-section along line A-A of the sample shown in FIG. **19** in Y-Z plane;

FIG. **21** shows a cross-sectional view of a sample having a surface morphology pseudo-periodic with a baseline grating profile in Y-Z plane;

FIG. **22** shows a cross-sectional view of a sample having a surface morphology pseudo-periodic with an undercut pseudo-periodic grating profile Y-Z plane;

FIG. **23** shows a cross-sectional view of a sample having a surface morphology pseudo-periodic with a top-rounding pseudo-periodic grating profile Y-Z plane;

FIG. **24** shows a cross-sectional view of a sample having a surface morphology pseudo-periodic with an 86° sidewall angle pseudo-periodic profile Y-Z plane;

FIG. **25** shows an intensity plot of a simulated electron wave-function modulus in Y-Z-plane as incident electrons are reflected;

FIG. **26** shows a graph of reflectivity versus reflection angle at azimuthal angle pseudo-periodic of 0°;

FIG. **27** shows a graph of reflectivity versus reflection angle at azimuthal angle pseudo-periodic of 0.25°;

FIG. **28** shows a graph of reflectivity versus azimuthal angle pseudo-periodic at reflection angle of 0.40°; and

FIG. **29** shows a graph of reflectivity versus reflection angle at a roll angle pseudo-periodic of 48.0°.

DETAILED DESCRIPTION

A detailed description of one or more embodiments is presented herein by way of exemplification and not limitation.

It has been discovered that an electron reflectometer and process for performing shape metrology provide electron reflectometry (ER) for measurement or determination of nanoscale dimensions in three dimensions at a surface with small-angle electron reflection. According to Fresnel's law, electrons have a high reflectivity from a surface at an electron energy from 5 kiloelectron volts (keV) to 100 keV at a glancing angle of less than 1° with respect to a plane of the surface. Moreover, the electron reflectometer overcomes reliance by reflective high energy electron diffraction (RHEED) on diffraction spots to determine atomistic surface structure and similar reliance by reflective small angle electron scattering (RSAES) to determine nanoscale shape morphology. Advantageously and unexpectedly, the electron reflectometer and processes measure nanoscale dimensions from intensity information of specularly reflected and non-specularly reflected electrons.

In an embodiment, with reference to FIG. **1**, FIG. **2** and FIG. **6** through FIG. **17**, electron reflectometer **200** includes sample stage **210**. Sample stage **210** receives sample **212**; disposes sample **212** in a position to be analyzed; and in conjunction with source collimator **232** and detection collimator **242** provides pitch rotation **214** through pitch angle **238** to sample **212** about pitch axis **216**; provides roll rotation **218** through roll angle **258** to sample **212** about roll axis **220**, wherein pitch axis **216** is perpendicular to and independent of roll axis **220**; and provides azimuthal rotation **222** through azimuthal angle **262** to sample **212** about azimuthal axis **224**, such that sample **212** can be rotated into a measurement position. Electron reflectometer **200** also includes source **226** that produces source electrons **230** directed toward sample **212**. Source collimator **232** is interposed between source **226** and sample stage **210** and receives source electrons **230**; collimates source electrons **230**; and produces incident electrons **234** from source electrons **230** in response to collimating source electrons **230** that travel along an incident direction **286** that is inclined at incident angle **228** with respect to sample stage **210**, wherein incident angle **228** is adjustable from 0° to 5° relative to a plane through pitch axis **216** and roll axis **220**. Source collimator **232** includes an electron lens **233** and source transmission aperture **236** bounded by aperture boundary wall **246** and has incident angular width **264** from 0.002° to 5°. Detection collimator receives reflected electrons **240** that are produced from incident electrons **234** reflected by sample **212**, collimates reflected electrons **240** by selecting reflected electrons **240** that travel along detection direction **288**, and produces collimated reflected electrons **250** from reflected electrons **240** in response to collimating reflected electrons **240**. Detection collimator **242** can include detection transmission aperture **244** having detection angular width **268** from 0.002° to 5°. It is contemplated that detection angle **248** is adjustable from 0° to 5° relative to the plane through pitch axis **216** and roll axis **220**. Electron reflectometer **200** also includes electron detector **252** that receives collimated reflected electrons **250**, wherein electron detector **252** is disposed such that detection collimator **242** is interposed between sample stage **210** and electron detector **252** or as part of a combined detection collimator **242** and electron detector **252**, e.g. as depicted in FIG. **5**.

FIGS. **6** through **11** show an embodiment of electron reflectometer **200** that includes mechanically actuated sample stage **210** to perform rotations and adjust electron directions. In FIGS. **6-17**, roll angle=0°, and azimuthal angle=0°. FIGS. **12** through **16** show an embodiment of electron reflectometer **200** that includes scanning coils **298** to perform rotations and adjust electron directions.

In an embodiment, electron reflectometer **200** includes energy filter **254** that receives collimated reflected electrons **250** from detection collimator **242**; filters collimated reflected electrons **250** based on an energy of collimated reflected electrons **250**; and communicates collimated

reflected electrons **250** to electron detector **252** based on the energy of collimated reflected electrons **250**.

In an embodiment, electron reflectometer **200** includes energy filter **254** that receives collimated reflected electrons **240**; filters collimated reflected electrons **240** based on an energy of collimated reflected electrons **240**; and communicates collimated reflected electrons **240** to detection collimator **242** based on the energy of reflected electrons **240**.

In an embodiment, electron reflectometer **200** includes analyzer **260** that receives detector signal **256** from electron detector **252**; analyzes detector signal **256**; and determines surface morphology **270** of sample **212**.

With regard to axes in several of the figures, coordinates (x, y, z) form an orthogonal coordinate system fixed to electron reflectometer **200**. Electron reflectometer **200** has three rotation axes, i.e. a pitch axis, a roll axis, and an azimuthal axis. At a zero-angle setting, i.e. pitch angle=0°, roll angle=0°, and azimuthal angle=0°, the three rotation axes coincide with the coordinate axes of electron reflectometer **200**, with x-axis along the roll axis, the y-axis along the pitch axis, and the z-axis along the azimuthal axis. When not in the zero-setting, the rotation axes can rotate relative to the coordinate axes of electron reflectometer **200**. Coordinates (X, Y, Z) are an orthogonal coordinate system fixed to a sample.

It is contemplated that sample stage **210** can include linear x-y stage **296** to provide positioning of sample **212** to select the measured region of the sample **212**; height adjustment stage **299** to align the sample **212** with the incident electrons **234**; pitch goniometer **290** to provide pitch rotation **214** about the pitch axis **216**; roll goniometer **292** to provide roll rotation **218** of sample **212** about the roll axis **220**; rotation stage **294** to provide azimuthal rotation **222** about azimuthal axis **224**; and a means of securing the sample **212**. It is contemplated that sample stage **210** can be manual, can be motorized, can be comprised of one multiaxial goniometric stage and can be comprised of combined stages and goniometers mounted one upon another.

In electron reflectometer **200**, sample **212** can include a surface **274** that has an average orientation and normal direction and can have three-dimensional or patterned solid structure with a dimension smaller than 100 nm. Sample **212** can be an etched solid wafer such as a Si wafer or GaAs wafer, a substrate **272** with deposited material such as a thin film including metal films and photo-resist that can be etched to provide nanoscale patterning. With reference to FIG. **18**, FIG. **19**, and FIG. **20**, sample **212** can include substrate **272** having surface **274** upon which surface member **278** are disposed. Surface member **278** and substrate **272** can be a monolithic structure or an assemblage of independent components coupled together and in communication. A plurality of surface members **278** can be arranged in pattern **276** that can include lines or a curved feature. Patterns **276** can be periodic arrays of surface members **278** separated at pitch P and can have height H, width W (e.g., W**1**, W**2**, and the like), sidewall angle **295**, undercut **291**, top-rounding **293**, and the like. A plurality of surface members **278** can also be arranged randomly or pseudo-periodically. Substrate **272** can include Si wafers, Silicon on oxide (SOI) wafers, GaAs wafers, and sapphire wafers. Moreover, wafers can be a variety of sizes as well as diced chips. Further, surface member **278** can be of the same or different material than substrate **272** and surface **274** and can include photo-resist, oxide, metal, polymer, grown nanostructures such as nanowires, and condensed nanomaterials such as quantum dots to provide electronic, optical or chemical properties and functions. Surface members **278** can have dimensions as small as 1 nm. It is contemplated that only dimensions less than 100 nm will be measurable so that a contemplated test grating might have long lines of deposited material much longer than 100 nm, but also have width and/or height smaller than 100 nm so that only the width and height are measurable by electron reflectometry. A number of surface members **278** can be selected. Surface members **278** or patterns **276** to be measured can be chosen based on their technological or scientific interest or deliberately constructed as test patterns. It is contemplated that most accurate and precise measurements will result from patterns **276** that are periodic or pseudo-periodic. Larger areas will enhance measurement statistics and in some instances, will enhance the current of collimated reflected electrons **250**. It is contemplated that measured areas determined by incident footprint **265** will have linear dimensions ranging from 10 μm to 500 μm, and that patterns **276** should be as large or larger than the measured area so that reflected electrons **240** are only produced from the pattern **276** and nowhere else. It is contemplated that the electron reflectometer **200** will be most useful for measuring the pitch P of a pattern **276** when P ranges from 2 nm to 100 nm, for measuring the height H of pattern **276** surface members **278** when H ranges from 1 nm to 100 nm and to measure the width W of pattern **276** surface members **278** when W ranges from 1 nm to 100 nm. It is contemplated that geometry of undercut **291** and similar features such as top-rounding **293** can be measured most precisely when the feature size ranges from 0.5 nm to 100 nm, specifically 0.5 nm to 10 nm, and more specifically from 0.5 nm to 5 nm. It is contemplated that the electron reflectometer **200** is extremely sensitive to sidewall angle **295** over the entire range of possible values including large overhangs.

In electron reflectometer **200**, pitch rotation **214** can include rotating sample **212**, roll axis **200**, and azimuthal axis **224** together about pitch axis **216** by pitch angle **238** relative to incident direction **286** and detection direction **288** together. Moreover, pitch rotation **214** can include active rotation wherein sample **212**, roll axis **220**, and azimuthal axis **224** together undergo rotational motion about pitch axis **216**; passive rotation; wherein incident direction **286** and detection direction **288** together undergo rotational motion in opposite sense about pitch axis **216**; and a combination thereof to provide total pitch angle **238**. Pitch rotation **214** can dispose sample **212** and instrument **200** for measurement and to adjust reflection conditions during measurement. Moreover, pitch rotation **214** can be coarsely adjustable and can be finely adjustable. Pitch rotation **214** can be provided by a fixed sample stage **210**, by set screws and the like, by a pitch goniometer **290**, by a combination of stages and goniometers, and by adjustment to and redisposition of source collimator **232** and detection collimator **242**.

In electron reflectometer **200**, pitch angle **238** can include a coarsely adjustable value, and a finely adjustable value respectively to align the elements of the electron reflectometer **200** and change incident angle **228** and detection angle **248**. Coarse adjustment of pitch angle **238** can be from 0° to 90°. Fine adjustments of pitch angle **238** can be from 0° to 10°, specifically from 0° to 5° and more specifically from 0° to 2°. Fine adjustment of pitch angle **238** increments can be from 0.0001° to 0.1°, specifically 0.0001° to 0.01°, and more specifically from 0.0001° to 0.001°. Adjustment of pitch angle **238** can be performed in steps and can be performed continuously over time.

In electron reflectometer **200**, pitch axis **216** can be fixed in orientation relative to the entire electron reflectometer **200**, can vary in orientation with calibrations, can be mov-

ably disposed as needed to properly dispose the sample **212** and can change direction by passive roll rotation **218** and by passive azimuthal rotation **222**. Moving pitch axis **216** can be performed by height adjustment stage **299** and by adjusting source collimator **232** to redirect incident electrons **234**. Moreover, pitch axis **216** is perpendicular to roll axis **220**, is perpendicular to azimuthal axis **224** when roll angle **258**=0°, and intersects roll axis **220** and azimuthal axis **224** at sample surface **274** where incident electrons **234** are directed by source collimator **232**.

In electron reflectometer **200**, roll rotation **218** can include rotating sample **212** and azimuthal axis **224** together about roll axis **218** by roll angle **258** relative to pitch axis **216**, incident direction **286**, and detection direction **288** together. Moreover, roll rotation **218** can include active rotation wherein sample **212** and azimuthal axis **224** together undergo rotational motion about roll axis **218**; passive rotation; wherein pitch axis **216**, incident direction **286**, and detection direction **288** together undergo rotational motion in opposite sense about roll axis **218**; and a combination thereof to provide total roll angle **258**. Moreover, roll rotation **218** can be fixed, can be coarsely adjustable and can be finely adjustable. Roll rotation **218** can be provided by sample stage **210** via a fixed stage, set screws and the like, by a roll goniometer **292**, by a combination of stages and goniometers, and can be provided by adjustment and by redisposition of source collimator **232** and detection collimator **242**.

In electron reflectometer **200**, pitch angle **258** can include a fixed value, a coarsely adjustable value, and a finely adjustable value to align the elements of the electron reflectometer **200** and to facilitate measurements that require non-zero roll. Coarsely adjusted roll angle **258** can be from −90° to 90°, specifically from −60° to 60°, and more specifically from −30° to 30°. Fine adjustments of roll angle **258** can be from −10° to 10°, specifically from −5° to 5° and more specifically from −2° to 2°. Fine adjustment increments in roll angle **258** can be from 0.0001° to 0.1°, specifically 0.0001° to 0.01°, and more specifically from 0.0001° to 0.001°. Adjustments in roll angle **258** can be performed in steps and can be performed continuously over time. Roll angle **258** is equal to angle between pitch axis **216** and azimuthal axis **224** subtracted from 90°.

In electron reflectometer **200**, roll axis **220** can be fixed in orientation relative to the entire electron reflectometer **200**, can vary in orientation with calibrations, can be movably disposed to dispose sample **212** for measurement, and can rotate as a result of active pitch rotation **214** and passive azimuthal rotation **222**. Moving roll axis **220** can be performed by adjusting source collimator **232** to redirect incident electrons **234**. Moreover, roll axis **220** is perpendicular to both pitch axis **216** and azimuthal axis **224**, is ideally tangent to the sample surface **274**, and intersects pitch axis **216** and azimuthal axis **224** at sample surface **274** where incident electrons **234** are directed by source collimator **232**.

In electron reflectometer **200**, azimuthal rotation **222** can include rotating sample **212** about azimuthal axis **224** by azimuthal angle **262** relative to pitch axis **216**, roll axis **220**, incident direction **286**, and detection direction **288** together. Moreover, azimuthal rotation **222** can include active rotation; wherein sample **212** undergoes rotational motion about azimuthal axis **224**; passive rotation; wherein pitch axis **216**, roll axis **200**, incident direction **286**, and detection direction **288** together undergo rotational motion in opposite sense about azimuthal axis **224**; and a combination thereof to provide total azimuthal angle **262**. Moreover, azimuthal rotation **222** can be fixed, can be coarsely adjustable and can be finely adjustable. Azimuthal rotation **222** can be provided by sample stage **210** via a fixed stage, set screws and the like, by a rotation stage **294**, by a combination of stages and goniometers, and can be provided by adjustment of source collimator **232** and detection collimator **242**.

In electron reflectometer **200**, azimuthal axis **224** can be fixed in orientation relative to the entire electron reflectometer **200**, can vary in orientation with calibrations, can be movably disposed as needed to properly dispose the sample **212** and can rotate as a result of passive pitch rotation **214** and passive roll rotation **218**. Moving azimuthal axis **224** can be performed by adjusting source collimator **232** to redirect incident electrons **234**. Moreover, azimuthal axis **224** is perpendicular to roll axis **220**, is perpendicular to pitch axis **216** when roll angle **258**=0°, intersects pitch axis **216** and roll axis **220** at sample surface **274** where incident electrons **234** are directed by source collimator **232**, and is ideally perpendicular to sample surface **274**.

In electron reflectometer **200**, pitch angle **262** can include a fixed value, a coarsely adjustable value, and a finely adjustable value to align the elements of the electron reflectometer **200** and to facilitate ER measurements that require azimuthal rotation **222**. Coarse adjustment of azimuthal angle **262** can be from −180° to 180°, specifically from −90° to 90°, more specifically from −45° to 45°. Fine adjustment of azimuthal angle **262** can be from −10° to 10°, specifically from −5° to 5° and more specifically from −2° to 2°. Fine adjustment increments can be from 0.0001° to 0.1°, specifically 0.0001° to 0.01°, and more specifically from 0.0001° to 0.001°. Adjustments can be performed in steps and can be performed continuously over time.

In electron reflectometer **200**, source **226** can include a variety of electron source types used in other applications including: a tungsten thermionic source, a LaB_6 thermionic source, a Schottky emission source and a cold field emission gun (FEG) to provide source electrons **230** directed toward source collimator **232**. The source **226** can include a monochromator and an electron lens **233**. The source **226** can provide source electrons **230** with kinetic energy ranging from 100 eV to 100 keV, specifically from 1 keV to 80 keV, and more specifically from 5 keV to 30 keV. The source **226** can have a brightness such that when combined with other elements of the electron reflectometer **200**, there will be sufficient current of collimated reflected electrons **250** to measure. Brightness of electrons can be roughly from 10^6 A m^{-2} rad^{-2} to 10^{14} A m^{-2} rad^{-2} depending on choice of electron source **226** and source settings. Moreover, source **226** can be fixed, calibrated and movable disposed as required by source collimator **232** to provide incident electrons **234** directed along incident direction **286**.

In electron reflectometer **200**, source electrons **230** can have a variety of kinetic energies and brightnesses chosen to provide currents of collimated reflected electrons **250** and detector signal **256**. Brightness of electrons can be roughly from 10^6 A m^{-2} rad^{-2} to 10^{14} A m^{-2} rad^{-2} depending on choice of electron source **226** and source settings. An energy of source electrons **230** can be 100 eV to 100 keV, specifically from 1 keV to 80 keV, and more specifically from 5 keV to 30 keV.

In electron reflectometer **200**, source collimator **232** can include an electron lens **233**, a scanning coil **298**, an electron stigmator and a source transmission aperture **236** to provide incident electrons **234** that travel toward sample **212** along incident direction **286** with incident angle **228** and incident angular width **264** to impinge upon sample surface producing an incident footprint **265**. With reference to FIG. **3**, source collimator **232** can refocus source electrons **230**, e.g.

by means of electrons lens **233**, to provide convergent beam as needed to provide incident angular width **264** and incident footprint **265**. With reference to FIG. **3**, source collimator **232** includes source transmission aperture **236** bounded by aperture boundary wall **246**, wherein source collimator **232** transmits some electrons through source transmission aperture **236** to provide electrons that propagate within incident angular width **264** of incident direction **286** and stops other electrons that would otherwise propagate beyond incident angular width **264**, e.g. by blocking. Source electrons **230** that pass through source transmission aperture **236** of source collimator **232** are incident electrons **234**. Source electrons **230** that are blocked by source collimator **232** can be referred to as blocked or discarded electrons **282**.

In electron reflectometer **200**, incident angle **228** is the angle between incident direction **286** and the plane through pitch axis **216** and roll axis **220**. Incident angle **228** can be varied by adjusting source collimator **232** and can be varied by changing pitch rotation **214**. Incident angle **228** can be from 0° to 5°, specifically from 0° to 2°, and more specifically from 0° to 1°.

In electron reflectometer **200**, incident angular width **264** is the convergence angle or divergence angle of incident electrons **234** and can include a single value specifying the angular width of beam of incident electrons **234** with a circular cross-section, and can include two or three values to specify individually the angular width of an a beam of incident electrons **234** that has elliptical cross-section, rectangular cross-section and the like. Incident angular width **264** limits the angular variation of directions of travel of incident electrons **234** from incident direction **286**. Incident angular width **264** can be fixed or variable. It is contemplated that incident angular width **264** can be changed by selecting a source transmission aperture **236** and by adjusting an electron lens **233**. Incident angular width **264** can greatly affect angular resolution of ER measurements, incident footprint **265**, and current of incident electrons **234** and consequently currents of reflected electrons **240** and collimated reflected electrons **250**. Small value of incident angular width **264** can improve angular resolution electron reflectometer, reduce the size of incident electron footprint **265**, and simplify data analysis; however, reducing incident angular width **264** also reduces current of incident electrons **234** in accordance with the law of conservation of brightness, and for some sizes of incident footprint **265** may be limited by electron diffraction. Choice of incident angular width **264** can be made in consideration of other elements of electron reflectometer **200** including: incident electron footprint **265**, detection angular width **268**, electron detector **252** and analyzer **260**. Values of incident angular width **264** can be from 0° to 5°, specifically from 0° to 0.5°, and more specifically from 0° to 0.01°.

In electron reflectometer **200**, incident electrons **234** can have a variety of kinetic energies and brightnesses to provide angular resolution and currents for measurement process. Moreover, incident electrons **234** can be directed toward different areas of sample **212** by movably disposing sample **212** and by redirecting incident electrons **234** with source collimator **232**. Brightness of electrons can be roughly from 10^6 A m^{-2} rad^{-2} to 10^{14} A m^{-2} rad^{-2} depending on choice of electron source **226** and source settings. Energy of source electrons **234** can be 100 eV to 100 keV, specifically from 1 keV to 80 keV, and more specifically from 5 keV to 30 keV. Incident electrons **234** impinge on sample **212** at incident angle **228** with incident angular width **264** to produce an incident footprint **265** on sample surface **274**.

In electron reflectometer **200**, source transmission aperture **236** selects from source electrons **230** those electrons that will be transmitted as incident electrons **234**. source transmission aperture **236** can be a transparent region to source electrons **230** in a component that is otherwise opaque to source electrons **230** to exclude source electrons **230** with trajectories that would deviate from incident direction **286** by more than incident angular width **264**. Source transmission aperture **236** can be a hole, a notch, and a slit in a metal strip. Examples of usable metal strips include Pt/Ir strips, Mo strips and Au strips. Source transmission aperture **236** can include a space between a plurality of opaque components. Source transmission aperture **236** can be a region that is rendered transparent to source electrons **230** by thinning and the like.

In electron reflectometer **200**, incident footprint **265** is region of sample surface **274** illuminated by incident electrons **234**. It's size and shape can be provided by selecting and adjusting electron source **226**, adjusting distance between source **226** and source collimator **232**, adjusting focal length of electron lens **233** in collimator, and by adjusting focal lengths of multiple electron lenses **233**. Moreover, incident footprint **265** can determine which region of sample surface **274** is measured, and can be moved and reshaped by adjusting and by movably disposing source collimator **232**, source transmission aperture **236**, scanning coil **298**, incident angular width **264**, incident angle **228** and by movably disposing sample **212** with motion of sample stage **210**, by linear x-y stage **296**, linear stage **297** and the like.

In electron reflectometer **200**, reflected electrons **240** can include incident electrons **234** that are reflected elastically and inelastically from sample **212**, including electrons that are specularly reflected, diffracted, and diffusely reflected, and they can be contaminated with secondary electrons that are scattered out of sample **212**. Moreover, elastically reflected electrons will have identical energies to incident electrons **234**, while inelastically reflected electrons can have energies that differ from energies of incident electrons **234**. Reflected electrons **240** are received by detection collimator **242** to produce collimated reflected electrons **250**.

In electron reflectometer **200**, detection collimator **242** can include electron optical components: scanning coil **298** and electron lens **233**, a detection transmission aperture **244** to select from reflected electrons **250** those electrons with direction of travel that are sufficiently close to the detection direction **288** as determined by the detection angular width **268** and that originate from incident footprint **265** on sample **212**. Moreover, detection collimator can be part of electron detector **252**. For example, with regard to FIG. **5** a pixelated area detector as shown or perhaps a phosphor with pixelated camera can function as both electron detector **252** and detection collimator **242** by selecting which pixels will contribute to measured reflection intensity.

In electron reflectometer **200**, detection transmission aperture **244** can include a region that is transparent or sensitive to reflected electrons **240** in a component that is otherwise opaque or insensitive to reflected electrons **240** to exclude reflected electrons **240** that have trajectories that deviate from detection direction **288** by more than detection angular width **268**. Detection transmission aperture **244** can be a hole, a notch, and a slit in a metallic strip. Examples of metallic strips include Pt/Ir, Mo, and Au strips. With Reference to FIG. **6** through FIG. **11**, detection transmission aperture **244** can include a space between opaque components. Detection transmission aperture **244** can be abstract as

in pixels in an area detector as in FIG. **5** that are selected for post processing and can be the sensitive area of a detector such as a geometrically limited phosphor.

In electron reflectometer **200**, detection angle **248** is angle between detection direction **288** selected by detection collimator **242** and the plane through pitch axis **216** and roll axis **220**. Detection angle **248** can be varied by settings and redisposition of detection collimator **242** and by changing pitch rotation **214**. Incident angle **228** can be from 0° to 5°, specifically from 0° to 2°, and more specifically from 0° to 1°.

In electron reflectometer **200**, detection angular width **268** is the convergence angle or divergence angle of reflected electrons **234** to be selected for collimation by detection collimator **242**; and can include a single value specifying the angular width of beam of collimated reflected electrons **250** with a circular cross-section, and can include two or three values to specify individually the angular width of a beam of collimated reflected electrons **250** with elliptical cross-section and the like. Detection angular width **268** limits the selection of reflected electrons **240** to be transmitted as collimated reflected electrons **250** by their angular variation of directions of travel from detection direction **288**. Detection angular width **268** can be fixed or variable. It is contemplated that detection angular width **268** can be changed by selecting a detection transmission aperture **244** for a given measurement or by activating and deactivating pixels in an area detector as shown in FIG. **5**. Detection angular width **268** can greatly affect angular resolution of ER measurements and current of collimated reflected electrons **250**. Small value of detection angular width **268** can improve angular resolution of electron reflectometer and simplify data analysis; however, reducing detection angular width **268** also reduces current of collimated reflected electrons **250** in accordance with the law of conservation of brightness. Choice of detection angular width **268** can be made in consideration of other elements of electron reflectometer **200** including: incident angular width **264**, incident electron footprint **265**, electron detector **252** and analyzer **260**. Values of 268 can be from 0° to 5°, specifically from 0° to 0.05°, and more specifically from 0° to 0.01°.

In electron reflectometer **200**, collimated reflected electrons **250** are produced by detection collimator **242** from reflected electrons **240** to be selectively detected by electron detector **252**. Collimated reflected electrons **250** can maintain travel directions of selected reflected electrons **240**, and can have altered directions of travel as part of the collimation process or as a byproduct of collimation. It is contemplated that reflected electrons **240** and collimated reflected electrons **250** independently include elastically scatted electrons, inelastically scatted electrons, specularly reflected electrons, non-specularly reflected electrons, secondary electrons, or a combination of the foregoing types of reflected electrons. With reference to FIG. **4**, detection collimator **242** includes detection **244** bounded by aperture boundary wall **246**, wherein detection transmission aperture **244** transmits reflected electrons **240** that propagate within detection angular width **268** and does not transmit reflected electrons **240** that propagate beyond detection angular width **268**, e.g., by blocking. Reflected electrons **240** that are not transmitted by detection collimator **242** can be referred to as blocked or discarded electrons **284**. Collimated reflected electrons **250** are reflected electrons **240** that are transmitted through detection transmission aperture **244** of detection collimator **242**. With reference to FIG. **5**, reflected electrons **240** can be collimated by a combined detection collimator **242** and electron detector **252** to produce collimated reflected electrons **250** by a virtual process. In FIG. **5**, a pixelated detector is shown that serves as both detection collimator **242** and electron detector **252**. Detection transmission aperture **244** is comprised a subset of all pixels **247** that are activated or counted. Boundary between counted or activated pixels **247** and uncounted or deactivated pixels **247** form a virtual aperture boundary wall **246**.

In electron reflectometer **200**, electron detector **252** can measure current of collimated reflected electrons **250**, can measure kinetic energy current of collimated reflected electrons **250**, and can include a phosphor screen, a camera, a scintillator, a photomultiplier, a solid state diode detector, a Faraday cup, an electrode and an electrometer. Moreover, electron detector **252** is sensitive to anticipated currents of collimated reflected electrons **250** that are anticipated to be a fraction of current of incident electrons **234**; wherein the ratio of current of collimated reflected electrons **250** to current of incident electrons **234** can be from 10^{-10} to 1, specifically 10^{-6} to 1, more specifically from 10^{-3} to 1.

In electron reflectometer **200**, energy filter **254** selects electrons for detection according to their kinetic to discriminate between electrons reflected elastically, electrons reflected inelastically, between electrons reflected by the various modes inelastic scattering and from secondary electrons. Energy filter **254** can include a retarding mesh, a magnetic prism, a slit-filter located at a dispersion plane in combination with other electron optics, and the like. Energy filter can be interposed between sample stage **210** and detection collimator **242** to filter reflected electrons **240**, and can be interposed between detection collimator **242** and electron detector **252** to filter collimated reflected electrons **252**.

In electron reflectometer **200**, analyzer **260** can include a dedicated computer or instrument that can compare and contrast detector signal **256** to an expected signal shape, compare and contrast detector signal **256** to a variety of hypothesized signal shapes, perform statistical regression of detector signal **256** to a physical model to determine physical geometry of sample **212** and surface morphology **270**, employ machine learning algorithms to determine physical geometry of sample **212** and surface morphology **270**. Analyzer **260** can include analog to digital converter, computer components, can communicate with electronic hardware controlling electron reflectometer **200**, and can be directly integrated with electronic hardware controlling electron reflectometer **200**.

In electron reflectometer **200**, surface morphology **270** can be a qualitative or quantitative description of sample surface **274**, surface members **278** and groups and patterns **276** of surface members **278**: including measurement of pitch P, height H, width W, sidewall angle **295**, the presence, absence and size of small features including undercut **291** and top-rounding **293**, statistical characterization such as densities of random arrays, disorder including aperiodicity, pseudo-periodicity, pitch-walking, overall size-distributions of nanoparticles and any geometric property that can be quantified using stationary statistics such as densities, means, standard deviations, correlations and the like.

In an embodiment, a process for making electron reflectometer **200** with respect to FIG. **6** through FIG. **11** includes: providing a main body for environment and structural support of electron reflectometer **200**; disposing source **226** on one side of main body of electron reflectometer **200**; disposing source collimator **232** adjacent to source **226**; constructing sample stage **210**; disposing sample stage **210** interposed between source collimator **232** and anticipated detection collimator **242**; constructing detection collimator

242; disposing detection collimator 242 interposed between anticipated location of sample 212 on sample stage 210 and electron detector 252; disposing electron detector to receive and detect collimated reflected electrons 250.

Providing main body of electron reflectometer 200 includes constructing or customizing a vacuum chamber to provide mean-free-path of electrons large enough so that electron scattering away from sample does not render measurement impossible. An electron mean-free-path comparable to or larger than the distance from source 226 to detector 252 should be sufficient. Main body includes ports to allow power and signal wires to reach the same, and to allow insertion and removal of sample 212 and mounting of sample 212 upon sample stage 210 and includes ports and attachment points for other elements of electron reflectometer.

Disposing source 226 on main body of electron reflectometer 200 includes providing fixed or movable attachments and ensuring that source collimator 232 can receive source electrons 230. In embodiment depicted in FIG. 6 through FIG. 11, source 226 provides source electrons 230 mostly directed along incident direction 286.

Disposing source collimator 232 adjacent to source 226 includes disposing electron lenses 233 and source transmission aperture 236 so that they are aligned with electron source 226 and anticipated location of sample 212 to receive source electrons 230 and provide incident electrons 234 along incident direction 286. In embodiment depicted in FIG. 6-FIG. 11, components of source collimator 232 are all aligned to transmit electrons along incident direction 286.

Constructing sample stage 210 includes: assembling together pitch goniometer 290 to provide pitch rotation 214, roll goniometer 292 to provide roll rotation 218, optional height adjustment stage 298 for repositioning of sample 212; optional linear x-y stage 296 for repositioning of sample 212 in plane perpendicular to azimuthal axis 224; and rotation stage 294 to provide azimuthal rotation 222. Constructing sample stage 210 can anticipate size and shape of a sample 212 to leave space and range of motion to allow roll axis 220 to be aligned tangent to sample surface 274 and azimuthal axis 224 to be aligned perpendicularly to sample surface 274. It is contemplated that aligning pitch goniometer 290, roll goniometer 292, and rotation stage 294 so that their respective centers of rotation have a common point of intersection will help provide most precise and accurate pitch rotation 214, roll rotation 216, and azimuthal rotation 222.

Disposing sample stage 210 interposed between source collimator 232 and anticipated detection collimator 242 includes placement and alignment of sample stage 210 so that anticipated mounted sample 212 can receive from source collimator 232 incident electrons 234 traveling along incident direction 286 at point of common intersection of pitch axis 216, roll axis 220 and azimuthal axis 224. If sample stage 210 includes optional linear x-y stage 296 and height adjustment stage 299, sample stage 210 can be disposed so that range of motion of an anticipated sample surface 274 can move through this point of common intersection.

Constructing detection collimator 242 includes with reference to FIG. 6 and FIG. 10, disposing two Pt/Ir strips with thickness of 1 mm or a little more, side-by-side and separated by the distance needed to provide detection transmission aperture 244 with detection angular width 268, which is roughly the distance from the anticipated incident footprint 265 to the anticipated detection transmission aperture 244 multiplied by the desired detection angular width 268. Taking care that the roughness of aperture boundary wall 246 is small (<5% of the linear width of detection transmission aperture 244) will provide a more easily analyzed current of collimated reflected electrons 250.

Disposing detection collimator 242 interposed between anticipated location of sample 212 on sample stage 210 and electron detector 252 includes with regard to FIG. 6 and FIG. 10, aligning detection collimator 242 and detection transmission aperture 244 so as to receive reflected electrons 240 and produce collimated reflected electrons 250, specifically, detection collimator 242 can be disposed so that length of detection transmission aperture 244 is parallel to azimuthal axis 224 and centered about roll axis 220.

Disposing electron detector 252 to receive and detect collimated reflected electrons 250 includes placement and alignment of electron detector 252 so that it is sensitive to collimated reflected electrons 250 but not to other reflected electrons 240. Electron sensitive area of electron detector 252 can span the total anticipated range of angles of pitch rotation 214 and detection angle 248; wherein detection angle 248 is anticipated to have a range similar to range of pitch angle 238.

In an embodiment, a process for making electron reflectometer 200 with respect to FIG. 12 through FIG. 17 includes: providing a main body for environment and structural support of electron reflectometer 200; disposing source 226 on one side of main body of electron reflectometer 200; constructing and disposing source collimator 232 adjacent to source 226; constructing sample stage 210; disposing sample stage 210 interposed between source collimator 232 and anticipated detection collimator 242; constructing detection collimator 242 from scanning coils 298 and electron-opaque material so as to provide detection angular width 268 and enable operation of electron reflectometer scan modes; disposing detection collimator 242 interposed between anticipated location of sample 212 on sample stage 210 and electron detector 252; disposing electron detector 252 to receive and detect collimated reflected electrons 250.

Providing main body of electron reflectometer 200 includes constructing or customizing a vacuum chamber to provide mean-free-path of electrons large enough so that electron scattering away from sample does not render measurement impossible. An electron mean-free-path comparable to or larger than the distance from source 226 to detector 252 should be sufficient. Main body includes ports to allow power and signal wires to reach the same, and to allow insertion and removal of sample 212 and mounting of sample 212 upon sample stage 210 and includes attachment points for other elements of electron reflectometer.

Disposing source 226 on main body of electron reflectometer 200 includes providing fixed or movable attachments and ensuring that source collimator 232 can receive source electrons 230. In embodiment depicted in FIG. 12-FIG. 17, source 226 provides source electrons 230 mostly directed about roll axis 220 that is coincident with central axis of source collimator 232.

Constructing and disposing source collimator 232 adjacent to source 226 includes disposing electron lenses 233 with optical axes aligned about roll axis 220, disposing source transmission aperture 236 centered on and perpendicular to roll axis 220 so as to allow electrons to travel down roll axis and scanning coils 298 centered around roll axis 220 so as to deflect electrons off of roll axis 220 onto and travelling along a potential incident direction 286.

Constructing sample stage 210 includes disposing a stable support for a range of intended type of sample 212. Sample stage 210 can include linear stage 297 for repositioning of

sample **212** perpendicular to plane through roll axis **220** and azimuthal axis **224**. Sample stage **210** can include additional positioning and goniometric capability to help with calibration including height adjustment stage **299**, pitch goniometer **290**, roll goniometer **292** and rotation stage **294**.

Disposing sample stage **210** interposed between source collimator **232** and anticipated detection collimator **242** includes placement and alignment of sample stage **210** so that anticipated mounted sample **212** can receive from source collimator **232** incident electrons **234** traveling along incident direction **286** at point of common intersection of pitch axis **216**, roll axis **220** and azimuthal axis **224** and allow the normal direction to the sample surface **274** to be aligned with azimuthal axis **224**. It is contemplated that small misplacements and misalignments can be corrected during calibration using adjustments to source collimator **232** and detection collimator **242**, and that large variations in shape and size of sample **212** can be accommodated if sample stage **210** is more versatile and includes height adjustment stage, linear x-y stages and goniometers.

Constructing and disposing detection collimator **242** interposed between anticipated location of sample **212** on sample stage **210** and electron detector **252** includes disposing a scanning coil **298** centered around and aligned with roll axis **220**, and disposing an electron-opaque barrier, for example a Pt/Ir strip or plate with thickness of 1 mm, that has a detection transmission aperture **244**. The size and shape of detection transmission aperture **244** can be chosen to provide a desired detection angular width **268**. For a circular detection transmission aperture **244**, a desired detection angular width **268** will result from choosing an aperture diameter equal to the desired detection angular width **268** multiplied by the distance between the detection transmission aperture **244** and the anticipated incident footprint **265**. If adjustments to the source collimator **232** are used to shift the position of the incident footprint **265**, the detection angular width **268** will vary accordingly. The actual detection angular width can vary with detection angle **248**.

Disposing electron detector **252** to receive and detect collimated reflected electrons **250** includes placement and alignment of electron detector **252** so that it is sensitive to collimated reflected electrons **250** but not to other reflected electrons **240**. FIG. **13**, FIG. **15** and FIG. **17** serve as a guide. Electron sensitive area of electron detector **252** is aligned to receive electrons transmitted through detection transmission aperture **244**. Since electrons will be deflected off the roll axis **220** by scanning coils **298**, electron sensitive area of electron detector **252** is large enough to accommodate anticipated variation of detection direction **288** and consequent variations in trajectories of collimated reflected electrons **250**.

Electron reflectometer **200** has numerous beneficial uses, including performing shape metrology. In an embodiment, a process for performing shape metrology of sample **212** includes: producing source electrons **230**; receiving, by source collimator **232**, source electrons **230** from source **226**; collimating, by source collimator **232**, source electrons **230**; producing, by source collimator **232**, incident electrons **234**; subjecting sample **212** disposed on sample stage **210** to incident electrons **234** from source collimator **232**; producing reflected electrons **240** from incident electrons **234** in response to receipt of incident electrons **234** by sample **212**; collimating, by detection collimator **242**, reflected electrons **240**; producing, by detection collimator **242**, collimated reflected electrons **250**; and receiving, by electron detector **252**, collimated reflected electrons **250** from detection collimator **242** to perform shape metrology of sample **212**.

The process for performing shape metrology can include disposing sample **212** on sample stage **210** so that incident footprint **265** will coincide with region of sample surface **274** to be measured.

Disposing sample **212** on sample stage **210** can include: securing sample **212** to sample stage **210** in desired position, and can include securing sample **212** to sample stage **210** and moving sample linearly with linear x-y stage **296**, linear stage **297**, height adjustment stage **299** and by linear motion of a multiaxial stage. Moreover, disposing sample **212** on sample stage **210** can include calibration of pitch angle **238**, roll angle **258**, and azimuthal angle **262** via pitch rotation **214** of sample **212** about pitch axis **216**, roll rotation **218** of sample **212** about roll axis **220**, and azimuthal rotation **222** of sample **212** about azimuthal axis **224**, and a combination of rotations. Disposing a Sample **212** with a well-defined sample surface **274** that has a well-defined normal direction, for example an etched semiconductor wafer, can include calibration of pitch angle **238** and roll angle **258** so that both angles are 0° when the plane through pitch axis **216** and roll axis **220** is parallel to sample surface **274**, and azimuthal axis **224** is perpendicular to surface normal. If sample **212** has an obvious azimuthal orientation such as an etched grating or a crystallographic direction, sample **212** can be disposed so that the grating lines or crystallographic direction are parallel to roll axis **220**. For this azimuthal orientation of sample **212**, azimuthal angle **262** can be recalibrated to 0°.

The process for performing shape metrology can include providing environment such as vacuum to provide mean-free-path of electrons long enough that additional electron scattering in gas or air does not distort or obscure angular dependence of electron reflectivity. An electron mean-free-path comparable to or larger than the distance from source **226** to detector **252** should be sufficient.

In the process for performing shape metrology, producing source electrons **230** includes adjusting source current and accelerating voltage to provide source electrons **230** with selected kinetic energy. Kinetic energy of source electrons **230** can be selected from the range of 100 eV to 100 keV, specifically from 1 keV to 80 keV and more specifically from 5 keV to 30 keV. Selection of kinetic energy can be performed by considering effect of energy on electron wavelength and consequent effects on angular resolutions and ranges of angular scans, vulnerability of sample **212** to damage by electrical current and energy, effect on anticipated reflectivity of sample **212** using Fresnel's law of reflectivity as a guide, and by effect of kinetic energy on electron mean-free-path in provided environment.

The process for performing shape metrology can include adjusting and redisposing source **226** and source collimator **232**, and selecting or changing source transmission aperture **236** to provide desired incident direction **286**, incident angle **288**, incident angular width **264**, and incident footprint **265**. Adjustments to source **226** and source collimator **232** can be performed at beginning of process for performing shape metrology and can be performed throughout process.

Adjusting and redisposing source **226** and source collimator **232** to provide desired incident direction **286**, incident angle **228**, incident angular width **264** and incident footprint **265** can include movably disposing source **226**, movably disposing source collimator **232**, adjusting focal length of an electron lens **233**, and adjusting deflection from a scanning coil **298**. Electron lens **233** can be adjusted to: magnify and de-magnify electron optical image of electron source **226** and to move electron optical image of electron source **226** along incident direction **286** to provide incident footprint

265 and incident angular width 264. A scanning coil 298 can be adjusted to move incident footprint 265 on sample surface 274 and to calibrate incident direction 286 and incident angle 228.

The process for performing shape metrology can include adjusting electron detector 252, detection collimator 242 and selecting or changing detection transmission aperture 244 to provide desired detection direction 288, detection angular width 268 and to receive reflected electrons 240 from measured area of sample surface 274. Adjustments of electron detector 252 and detection collimator 242 can be performed at start of process for performing shape metrology and can be performed throughout process. In some cases, detection transmission aperture 244 can be changed throughout process for performing shape metrology as well; for example, when detection transmission aperture 244 is provided by selecting and deselecting pixels on a camera.

Adjusting electron detector 252 and detection collimator 242 to provide desired incident angular width 264 and incident footprint 265 can include movably disposing source 226, movably disposing source collimator 232, adjusting deflection from a scanning coil 298.

The process for performing shape metrology can include performing pitch rotation 214 about pitch axis 216 through pitch angle 238, roll rotation 218 through roll angle 258 about roll axis 220 using, and azimuthal rotation 222 through azimuthal angle 262 about azimuthal axis 224, or a combination of the foregoing rotations.

Pitch rotation 214 can be active pitch rotation, passive pitch rotation, or a combination thereof.

Active pitch rotation can include rotating sample 212, roll axis 220 and azimuthal axis 224 through pitch angle 238 about pitch axis 216.

Passive pitch rotation can include rotating incident direction 286 and detection direction 288 through pitch angle 238 in the opposite sense of pitch rotation 214 about pitch axis 216.

Combination of active pitch rotation and passive pitch rotation can include a combination whose angles sum to a total that is equal to pitch angle 238.

Roll rotation 218 can be active roll rotation, passive roll rotation, or a combination thereof.

Active roll rotation can include rotating sample 212 and azimuthal axis 224 through roll angle 258 about roll axis 220.

Passive roll rotation can include rotating incident direction 286, detection direction 288 and pitch axis 216 through roll angle 258 in the opposite sense about roll axis 220.

Combination of active roll rotation and passive roll rotation can include a combination whose angles sum to a total that is equal to roll angle 258.

Azimuthal rotation 222 can be active azimuthal rotation, passive azimuthal rotation, or a combination thereof.

Active azimuthal rotation can include rotating sample 212 and through azimuthal angle 262 about azimuthal axis 224.

Passive azimuthal rotation can include rotating incident direction 286, detection direction 288, pitch axis 216 and roll axis 220 through azimuthal angle 262 in the opposite sense about azimuthal axis 224.

Combination of active azimuthal rotation and passive azimuthal rotation can include a combination whose angles sum to a total that is equal to azimuthal angle 262.

The process for performing shape metrology can include changing incident direction 286 to provide incident angle 228 between incident direction 286 plane through pitch axis 216 and roll axis 220 by performing pitch rotation 214, adjusting or movably disposing source collimator 232, adjusting or movably disposing source 226, or by combination thereof.

The process for performing shape metrology can include changing detection direction 288 to provide detection angle 248 between detection direction 288 and plane through pitch axis 216 and roll axis 220 by performing pitch rotation 214, adjusting or movably disposing detection collimator 242, adjusting or movably disposing electron detector 252, or combination thereof.

The process for performing shape metrology can include receiving, by energy filter 254, collimated reflected electrons 250 from detection collimator 242; filtering collimated reflected electrons 250 based on an energy of collimated reflected electrons 250; and communicating collimated reflected electrons 250 to electron detector 252 from energy filter 254 based on the energy of collimated reflected electrons 250.

The process for performing shape metrology can include receiving, by energy filter 254, reflected electrons 240; filtering reflected electrons 240 based on an energy of reflected electrons 240; and communicating reflected electrons 240 to detection collimator 242 from energy filter 254 based on the energy of reflected electrons 240.

The process for performing shape metrology can include receiving, by analyzer 260, detector signal 256 from electron detector 252; analyzing detector signal 256; and determining surface morphology 270 of sample 212 based on detector signal 256.

Also, the process for performing shape metrology can include performing reflection angle scans, azimuthal scans, roll scans and rolled reflection angle scans.

Performing reflection angle scans includes disposing and adjusting sample 212 and sample stage 210 to roll angle 258 of 0° and a selected azimuthal angle 262, usually also 0°. Incident angle 228 and detection angle 248 are adjusted to the same value and then varied together through a series of angles that can lie within the range from 0° to 5°, specifically from 0.1° to 2°, more specifically from 0.2° to 1° in discrete steps or in a ramp. Current of collimated reflected electrons 250 is measured and recorded for each step or throughout continuous ramp. Oscillations in current with scan angle can be analyzed to provide quantitative description of surface morphology 270. It is contemplated that current during reflection angle scan will oscillate with scan angle at a rate inversely related to height H of surface morphology 270, and that these oscillations are distorted, shifted, suppressed, and enhanced by the presence of other features such as undercut 291, top-rounding 293, and differences in sidewall angle 295. Discrete step size or slow ramp rate can be chosen to obtain a clear low-noise measurement for desired angular resolution of scan. Desired angular resolution can be determined by consideration of anticipated surface morphology 270. Larger height variations of surface morphology 270 requires finer angular resolution either to measure height or to get a clear measurement of fine features. As a heuristic guide, angular resolution expressed in radians should be no coarser than and preferably much less than the ratio of electron wavelength to height H. To illustrate, a reflection angle scan using electrons with wavelength of 12 pm on a grating with height H of 10 nm would require an angular resolution finer than 0.6 mrad or 0.034°. Additionally, maximum angle of reflection angle scan can be chosen according to desired feature sensitivity. Larger scan angles, i.e. larger incident angle 228 and detection angle 248 will provide sensitivity to smaller features. It is anticipated that sensitivity to features of small size like undercut 291 will be

enhanced if the range of pitch scan angles expressed in radians includes the ratio of electron wavelength to desired feature sensitivity. For example, to detect an undercut of diameter 1 nm with electrons of wavelength 12 pm, it is recommended to include the angle 6 mrad or 0.34° in a reflection angle scan. Moreover, decreasing incident angular width **264**, detection angular width **268** or both to required angular resolution will provide measured currents of collimated reflected electrons **250** vs. scan angle that are easier to analyze.

Performing azimuthal scans includes disposing and adjusting sample **212** and sample stage **210** to roll angle **258** of 0°. Incident angle **228** and detection angle **248** are adjusted to the same chosen value of constant reflection angle. While measuring current of collimated reflected electrons **250**, azimuthal rotation **222** is then performed by varying the azimuthal angle **262** through a series of angles that can lie within the range the range from −5° to 5°, specifically from −2° to 2°, more specifically from −1° to 1° in discrete steps or in a ramp. Oscillations in current with azimuthal angle **262** can be analyzed to provide quantitative description of surface morphology **270**. It is contemplated that current during azimuthal scan will oscillate at a rate inversely related to pitch P of surface morphology **270**, and that these oscillations are distorted, shifted, enhanced, and suppressed, by the presence of other features such as undercut **291**, top-rounding **293** and differences in sidewall angle **295**. The reflection angle of azimuthal scan can be chosen in a manner to provide sensitivity to desired features. As a heuristic guide to choosing reflection angle for azimuthal scan, it is anticipated that for an azimuthal scan to be sensitive to undercut **291**, the reflection angle of the azimuthal scan expressed in radians is recommended to be larger than half the ratio of incident electron wavelength to desired size sensitivity. For example, it is recommended that to detect an undercut **291** with diameter as small as 1 nm with an azimuthal scan of electrons with wavelength 12 pm, the reflection angle for an azimuthal should be larger than 6 mrad or 0.34°. Discrete step size or slow ramp rate can be chosen to obtain a clear low-noise measurement for desired angular resolution of scan. Desired angular resolution can be determined by consideration of anticipated surface morphology **270**. Larger values of pitch P of surface morphology **270** are best measured with finer angular resolution either to measure pitch P or to get a clear measurement of other features of surface morphology **270**. As a heuristic guide, it is recommended that angular resolution expressed in radians be no coarser than and preferably much less than the ratio of electron wavelength to pitch P of surface morphology **270**. To illustrate, an azimuthal scan using electrons with wavelength of 12 pm on a grating with pitch P of 100 nm would be most easily analyzed if the azimuthal scan is performed with an angular resolution finer than 0.12 mrad or 0.0069°. Moreover, decreasing incident angular width **264**, detection angular width **268** or both to required angular resolution will provide measured currents of collimated reflected electrons **250** vs. scan angle that are easier to analyze.

Performing roll scans includes disposing and adjusting sample **212** and sample stage **210** to azimuthal angle **262** of 0°. Incident angle **228** and detection angle **248** are adjusted to the same chosen value of constant reflection angle. While measuring current of collimated reflected electrons **250**, roll rotation **218** is then performed by varying the roll angle **258** through a series of angles that can lie within the range the range from −90° to 90°, specifically from −60° to 60°, more specifically from −30° to 30° in discrete steps or in a ramp. Oscillations in current with roll angle **258** can be analyzed to provide quantitative description of surface morphology **270**. It is contemplated that current during roll scan oscillate with roll angle **258** at a rate inversely effected by pitch P and height H of surface morphology **270**, and that these oscillations are distorted, shifted, enhanced, and suppressed by the presence of other features such as undercut **291**, top-rounding **293** and differences in sidewall angle **295**. The reflection angle of roll scan can be chosen in a manner to provide sensitivity to desired features. Higher reflection angles are anticipated to provide greater sensitivity to smaller features while lower reflection angles may provide clearer measurement of sidewall angle **295**. Discrete step size or slow ramp rate can be chosen to obtain a clear low-noise measurement for desired angular resolution of scan. As a heuristic guide, it is anticipated that angular precision of measurement of sidewall angle **295** will be limited by angular resolution of roll scan. Moreover, varying incident angular width **264**, detection angular width **268**, or both will tend to emphasize and deemphasize effects of various features of surface morphology **270**.

Performing rolled reflection angle scans includes disposing and adjusting sample **212** and sample stage **210** to selected roll angle **258** and an azimuthal angle **262** of 0°. Incident angle **228** and detection angle **248** are adjusted to the same value and then varied together through a series of angles that can lie within the range from 0° to 5°, specifically from 0.1° to 2°, more specifically from 0.2° to 1° in discrete steps or in a ramp. Current of collimated reflected electrons **250** is measured and recorded for each step or throughout continuous ramp. Oscillations in current with scan angle can be analyzed to provide quantitative description of surface morphology **270**. Selected roll angle **258** can lie in range of angles from −90° to 90°, specifically from −60° to 60°, more specifically from −30° to 30°. It is contemplated that current during rolled reflection angle scan will oscillate with scan angle at a rate inversely related to height H and pitch P of surface morphology **270**, and that these oscillations will be distorted and shifted by the presence of other features such as undercut **291**, top-rounding **293** and differences in sidewall angle **295**. Discrete step size or slow ramp rate can be chosen to obtain a clear low-noise measurement for desired angular resolution of scan. Desired angular resolution can be determined by consideration of anticipated surface morphology **270**. As a heuristic guide, angular resolution expressed in radians should be no coarser than and preferably much less than the ratio of electron wavelength to height H; should be no coarser than and preferably much less than the ratio of electron wavelength to pitch P. Moreover, decreasing incident angular width **264**, detection angular width **268** or both to required angular resolution will provide measured currents of collimated reflected electrons **250** vs. scan angle that are easier to analyze.

In the process for performing shape metrology, collimating, by source collimator **232**, source electrons **230** includes directing source electrons **230** toward intended area of sample **212** along incident direction **286** to provide incident footprint **265**, and providing incident angular width **264**. Source electrons **230** can be directed by use of electron optical elements that can include an electron lens **233**, a scanning coil **298** and a source transmission aperture **236**. Providing incident angular width **264** can include using a source transmission aperture **236** to block or capture electrons that deviate from incident direction **286** by more than incident angular width **264**.

In the process for performing shape metrology, producing, by source collimator **232**, incident electrons **234** includes

allowing electrons that are directed toward intended area of sample **212** along incident direction **286** to pass through collimator.

In the process for performing shape metrology, subjecting sample **212** disposed on sample stage **210** to incident electrons **234** from source collimator **232** includes ensuring sample **212** is correctly positioned and oriented and that incident footprint **265** is coincident with intended area to be measured of sample surface **274**.

In the process for performing shape metrology, producing reflected electrons **240** from incident electrons **234** in response to receipt of incident electrons **234** by sample **212** includes specular reflection of incident electrons **234** from sample surface **274** and surface members **278**, diffuse reflection of incident electrons **234** from sample surface **274** and surface members **278**, diffraction of incident electrons **234** by sample surface **274** and surface members **278**, elastic scattering of incident electrons **234** from sample **212**, inelastic scattering if incident electron **234** from sample **212**.

In the process for performing shape metrology, collimating, by detection collimator **242**, reflected electrons **240** includes preventing detection of those reflected electrons **240** whose trajectories deviate from detection direction **288** by more than detection angular width **268** and allowing those reflected electrons **240** whose trajectories are aligned with detection direction **288** as specified by detection angular width **268** to be detected as collimated reflected electrons **250**. Collimating reflected electrons **240** can include blocking some reflected electrons **240** while allowing other reflected electrons **240** to pass through a detection transmission aperture **244** to become collimated reflected electrons **250**, redirecting reflected electrons **240** in combination with use of a detection transmission aperture **244**, for example, by use of a scanning coil **298**, and by virtual means such as selectively keeping and discarding data from a pixelated area detector (e.g. as in FIG. **5**) in data post processing or combination thereof.

In the process for performing shape metrology, producing, by detection collimator **242**, collimated reflected electrons **250** includes selecting which reflected electrons **240** will be detected by electron detector **252** and which will not by creating an actual beam of collimated reflected electrons **250** that will be detected by electron detector **252**, or by immediately detecting selected reflected electrons **240** as collimated reflected electrons **250** in combination with electron detector **252**, for example selectively discarding data from a pixelated area detector in post processing.

In the process for performing shape metrology, filtering collimated reflected electrons **250** based on an energy of collimated reflected electrons **250** includes high pass filtering (selecting those electrons that have a kinetic energy higher than a specified value), low pass filtering (selecting electrons with a kinetic energy lower than a specified value) and band pass filtering (selecting electrons with kinetic energies falling within a specified range). High pass filtering can be used to reduce contributions to measured current of collimated reflected electrons **250** from inelastically scattered electrons and secondary elections. It is anticipated that measurements from high-pass filtered electrons will be most easily analyzed and modeled and have enhanced signal to noise ratio. Low pass filtering can be used to isolate electrons that have been produced by inelastic scattering allowing calibration of background and can be sensitive to material composition. Band pass filtering can provide more detailed information from inelastic scattering processes.

High pass filtering, low pass filtering and band pass filtering can include use of a retarding mesh, a magnetic prism, a slit-filter located at a dispersion plane in combination with other electron optics, and the like.

In the process for performing shape metrology, communicating collimated reflected electrons **250** to electron detector **252** from energy filter **254** based on the energy of collimated reflected electrons **250** includes directing filtered electrons toward sensitive area of electron detector **252**.

In the process for performing shape metrology, filtering reflected electrons **240** based on an energy of reflected electrons **240** includes high pass filtering (selecting those electrons that have a kinetic energy higher than a specified value), low pass filtering (selecting electrons with a kinetic energy lower than a specified value) and band pass filtering (selecting electrons with kinetic energies falling within a specified range). High pass filtering can be used to reduce contributions of reflected electrons **240** from inelastically scattered electrons and secondary elections and ultimately to reduce their contribution to collimated reflected electron **250** current. It is anticipated that measurements from high-pass filtered electrons will be most easily analyzed and modeled and have enhanced signal to noise ratio. Low pass filtering can be used to isolate electrons that have been produced by inelastic scattering allowing calibration of background and can be sensitive to material composition. Band pass filtering can provide more detailed information from inelastic scattering processes.

In the process for performing shape metrology, analyzing detector signal **256** includes tabulating and plotting signal vs independent variables including reflection angle, pitch angle **238**, roll angle **258**, and azimuthal angle **262**, typically by digital means.

In the process for performing shape metrology, determining surface morphology **270** of sample **212** based on detector signal **256** comparing dependence of signal **256** with measurements from reference samples, with simulations, with analytic calculations, noting periodicity and anomalies in data. For example, with reference to FIG. **26**-FIG. **29**, detector signal **256** has different dependence on azimuthal angle **262** when sample **212** has undercut **291**, top-rounding **293** and differences in sidewall angle **295**. This difference can be described as a change in ratios of peak intensity, phase shift of oscillations where peaks and troughs occur at different values of an independent variable or have different separations, and even suppressed oscillation peaks. In addition to noting qualitative features and performing graphical analysis, determining surface morphology **270** can include numerical regression to real-time simulations and to simulations performed in post-processing and to cataloged simulations, depending on time requirements and available resources, and machine learning-based methods.

Electron reflectometer **200** has numerous advantageous and beneficial properties. In an aspect, electron reflectometer **200** provides the ability to measure surface morphology **270** of a sample **212** with a combination of features that set it apart from other methods including strong interaction of with sample surface **274**, tunable size of incident footprint **265**, sensitivity to height H, width W, and other aspects of surface morphology **270** including sensitivity to subtle geometric features, requires little to no sample preparation, non-destructive measurement, ability to choose from a variety of electron sources and detectors, and ability to perform shape metrology by measuring current of collimated reflected electrons **250** for each disposition of sample **212** and incident direction **286**, as opposed to measuring a profile of scattering intensity through a range of solid-angles for each disposition of sample **212** and incident direction **286**.

Strong interaction with sample surface **274** is due to large scattering cross-sections of electrons when contrasted with x-rays and neutrons and large Fresnel reflectivity. Although frequently more difficult to analyze quantitatively, scattering from strongly interacting particles is predominantly sensitive to geometry avoiding obfuscation by other properties of sample **212** such as composition. The dependence of some measurement methods on multiple properties can be referred to as a parameter covariance problem.

Tunable size of incident footprint **265** including linear dimension ranges from widths of 20 μm to 100 μm allowing measurement that have statistically significant sampling and small spectral resolution while still small enough to be used on test structures that are size-constrained because of manufacturing considerations such as in the electronics industry where test-structures must frequently be limited to sacrificed areas such as dicing lanes. Moreover, tunable size of incident footprint **265** allows current density of incident electrons **234** to be modified without changing the total electron current, so that current density can be adjusted for considerations such as fragility and charging of sample **212**.

Sensitivity to height H results from interference between electrons reflected by the base of the sample surface **274** and surface members **278**, and electrons reflected by the top of the sample surface **274** and surface members **278**. This interference is possible because of the strong Fresnel reflectivity of incident electrons **234** at glancing angles and large electron scattering cross-sections.

Sensitivity to width W results from strong Fresnel reflectivity of incident electrons **234** at glancing angles and large electron scattering cross-sections resulting in dynamic scatting, also called multiple scattering.

Sensitivity to subtle geometric features includes sensitivity to undercut **291**, top-rounding **293**, sidewall angle **295**, and the like, and is depicted in FIG. **21**-FIG. **29** that describe a quantum simulation of dynamic reflection of electrons from a grating. FIG. **21** depicts an ideal grating cross-section that has no undercut **291**, no top-rounding **293** and a sidewall angle **295** of 88°. FIG. **22** depicts an almost ideal cross-section but with an undercut **291** of radius 0.5 nm. FIG. **23** depicts an almost ideal cross-section but with top-rounding **293** of radius 0.5 nm. FIG. **24** depicts an almost ideal cross-section but with a 2° reduction in sidewall angle **295**. FIG. **25** shows a simulated electron wavefunction of the type that occurs during reflection of incident electrons **234** to produce reflected electrons **240**. FIG. **26**-FIG. **29** show simulated electron reflectivity vs angle for various scan modes performed on gratings with four cross-sections show in FIG. **21**-FIG. **25**. FIG. **26** shows simulated current of collimated reflected electrons **250** vs. reflection angle data resulting from a reflection angle scan at azimuthal angle **262** of 0°. FIG. **27** shows simulated current of collimated reflected electrons **250** vs. reflection angle data resulting from a reflection angle scan at azimuthal angle **262** of 0.25°. FIG. **28** shows current of collimated reflected electrons **250** vs. azimuthal angle **262** during an azimuthal scan for a reflection angle of 0.40°. FIG. **29** shows current of collimated reflected electrons **250** vs. reflection angle during a rolled reflection angle scan for a roll angle **258** of 48.0°.

Requires little to no sample preparation because electron reflectometer **200** reflects electrons from sample surface **274**. Electron reflectometer **200** can measure surface morphology **270** under the same conditions required for Scanning Electron Microscopy. It is contemplated that test structures can be measured while on whole wafers with instrument dimensions and range of motion of sample stage **210** providing the only limits on size of sample **212**.

Non-destructive measurements result from qualities of electron reflectometry including: requires little or no sample preparation, currents and current densities of incidence electrons **234** can be adjusted, that Fresnel reflection of electrons at glancing angles deposits little energy in sample **212** because of effects that include: penetration by electrons takes place primarily by evanescent non-propagating waves over distances less than a few nm, and many inelastic scattering phenomena result in virtual scattering processes that enhance reflectivity of sample surface **274** instead of real inelastic scattering that deposits energy in sample **212** possibly causing damage.

Ability to perform shape metrology by measuring current of collimated reflected electrons **250** for each disposition of sample **212** and incident direction **286**, as opposed to measuring a profile of scattering intensity through a range of solid-angles for each disposition of sample **212** and incident direction **286** allows the measurement process to be simplified in contrast to other mentioned electron scattering methods such as RSAES. Other measurement processes require hyperfine angular resolution to determine diffraction spot locations while electron reflectometer **200** requires only the current of the collimated reflected electrons **250**; the direction of specular reflection is easy to predict as it depends on only the normal to the sample surface **274** and the incident angle **228**; it is independent of sample surface morphology **270**. Moreover, measurement of a single current greatly reduces requirements of angular resolution and enables a choice of electron detector **252** for specific needs such as low current density and allows a choice between an area detector and a point detector depending on applications. For the most demanding applications where one would like a combination of fine angular resolution, small incident footprint **265** and low current density, a high-sensitivity point detector can be used to compensate for the low current of incident electrons **234** to produce a useful current measurement of collimated reflected electrons **250**.

Electron reflectometer **200** advantageously and unexpectedly is capable of performing shape metrology by measuring changes in currents of collimated reflected electrons **250** that consist primarily of specularly reflected electrons, as the majority of reflected electrons **240** produced by non-specular reflection will fail to meet collimation criteria and will not contribute to the current of collimated reflected electrons **250**. Shape metrology can include inferring shape of sample **212** from intensity oscillations, regression of detailed electron reflection models to experimental data, differential comparisons to baseline experimental data to detect geometric features or defects, performing statistical inferences about random and quasi-periodic surface morphology **270** including: measurement of surface roughness, density and size of adsorbed nanoparticles, and the like, and interpreting currents of collimated reflected electrons **250** with machine-learning methods.

The articles and processes herein are illustrated further by the following Examples, which are non-limiting.

EXAMPLES

In the Examples, line gratings with features in nanometers were used. The Y-axis is defined along the direction parallel to the lines, the X-axis transverse to the lines and Z-axis is the direction along the height of the gratings. In this disclosure the line grating samples are placed on the reflectometer instrument at its zero-angle position with all three rotation angles set to zero, i.e. pitch angle=0°, roll angle=0°, and azimuthal angle=0°. With this angle setting and sample

placement, the sample Z-axis is along the azimuthal axis, X-axis along the roll axis and Y-axis long the pitch axis.

Example 1. Electron Reflectometry of Nanoscale Test Pattern Grating **276**

With regard to FIG. **18** through FIG. **29**, in example, we depict contemplated application of measurement of surface morphology **270** using electron reflectometer **200** to process refinement and quality control during nanoscale lithography. It is contemplated that a test pattern **276** grating includes long lines with lengths in the range from 10 μm to 10000 μm and with nanoscale cross-section as shown in FIG. **21**. Such a grating can be produced from a Si wafer via nanoscale lithographic techniques typical in use in the semiconductor and electronics industries. In example, baseline grating profile in FIG. **21** is the hypothetically desired product of nanoscale lithography. It has a pitch (P) of 15 nm, a height (H) of 20 nm, a width (W) at half-height of 7.5 nm, and a sidewall angle **295** of 88°. Contemplated deviations from desired outcome of baseline grating profile are depicted in FIG. **22**-FIG. **24**. Measurement of surface morphology **270** using electron reflectometer **200**, can detect even small deviations from the desired baseline grating profile, as illustrated here by simulating electron reflectometry using an electron kinetic energy of 5 keV, in various scan-modes including: reflection angle scan, azimuthal scan, and rolled reflection angle scan.

FIG. **22** depicts an undercut grating profile that differs from the baseline grating profile in FIG. **20** by virtue of having undercut **291** of grating walls **280** of radius 0.5 nm.

FIG. **23** depicts a top-rounding grating profile that differs from the baseline grating profile in FIG. **20** by virtue of having top-rounding **293** of grating walls **280** of radius 0.5 nm.

FIG. **24** depicts an 86° sidewall profile that differs from the baseline grating profile in FIG. **20** by virtue of having a sidewall angle **295** that is 2° less than the baseline value of 88°.

FIG. **25** shows an intensity plot of a simulated wave-function modulus when incident electrons **234** with kinetic energy of 5 keV impinge upon a line grating with baseline grating profile. Electron reflectometer **200** is set to have a reflection angle if 0.20°, pitch angle **238** of 0°, roll angle **258** of 0°, and an azimuthal angle of 0.33°. Even though the grating is energetically attractive to incident electrons **234**, their quantum wave nature results in a very large reflectivity, and there is almost no wave penetration. The baseline grating profile is clearly visible as the electron-deficient area in FIG. **25**. Small changes to the grating cross-section will distort the electron wave function changing the ratio of specularly reflected to non-specularly reflected electrons. Since specularly reflected electrons are the largest component of collimated reflected electrons **250**, electron reflectometer **200** can detect this difference.

FIG. **26** shows simulated data resulting from a reflection angle scan at azimuthal angle **262** of 0° for each of the four grating profiles. Depicted reflectivity oscillations have a rate that is sensitive to grating height H.

FIG. **27** depicts simulated data resulting from a reflection angle scan at azimuthal angle **262** of 0.25° for each of the four grating profiles. Depicted reflectivity oscillations are less clearly related to grating height H, but show greater sensitivity to the four different grating profiles, illustrating how electron-reflectometer **200** can detect small shape variations in grating profiles.

FIG. **28** depicts simulated data resulting from an azimuthal scan at reflection angle of 0.40° for each of the four grating profiles. Depicted reflectivity oscillations have angular frequency that varies inversely with line grating pitch P. Moreover reflectivities of each of the four grating profiles differ from one another illustrating how electron-reflectometer **200** can detect small shape variations in grating profiles.

FIG. **29** depicts simulated data resulting from a rolled reflection angle scan at roll angle of 48.0° for each of the four grating profiles. Depicted reflectivity oscillations are less clearly related to coarse geometric descriptions such as height H or pitch P, but they demonstrates how electron-reflectometer **200** can distinguish between grating profiles even when changes are small.

While one or more embodiments have been shown and described, modifications and substitutions may be made thereto without departing from the spirit and scope of the invention. Accordingly, it is to be understood that the present invention has been described by way of illustrations and not limitation. Embodiments herein can be used independently or can be combined.

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

All ranges disclosed herein are inclusive of the endpoints, and the endpoints are independently combinable with each other. The ranges are continuous and thus contain every value and subset thereof in the range. Unless otherwise stated or contextually inapplicable, all percentages, when expressing a quantity, are weight percentages. The suffix "(s)" as used herein is intended to include both the singular and the plural of the term that it modifies, thereby including at least one of that term (e.g., the colorant(s) includes at least one colorants). "Optional" or "optionally" means that the subsequently described event or circumstance can or cannot occur, and that the description includes instances where the event occurs and instances where it does not. As used herein, "combination" is inclusive of blends, mixtures, alloys, reaction products, and the like.

As used herein, "a combination thereof" refers to a combination comprising at least one of the named constituents, components, compounds, or elements, optionally together with one or more of the same class of constituents, components, compounds, or elements.

All references are incorporated herein by reference.

The use of the terms "a" and "an" and "the" and similar referents in the context of describing the invention (especially in the context of the following claims) are to be construed to cover both the singular and the plural, unless otherwise indicated herein or clearly contradicted by context. "Or" means "and/or." Further, the conjunction "or" is used to link objects of a list or alternatives and is not disjunctive; rather the elements can be used separately or can be combined together under appropriate circumstances. It should further be noted that the terms "first," "second," "primary," "secondary," and the like herein do not denote any order, quantity, or importance, but rather are used to

distinguish one element from another. The modifier "about" used in connection with a quantity is inclusive of the stated value and has the meaning dictated by the context (e.g., it includes the degree of error associated with measurement of the particular quantity).

What is claimed is:

1. An electron reflectometer comprising:

a sample stage that:

receives a sample comprising a sample surface;

disposes the sample in a position to be analyzed;

moves the sample surface to be positioned perpendicular to an azimuthal axis and coincident at a point of common intersection of a pitch axis, roll axis, and azimuthal axis;

provides a pitch rotation through a pitch angle to the sample about a pitch axis;

provides a roll rotation through a roll angle to the sample about a roll axis, the pitch axis being perpendicular to and independent of the roll axis; and

provides an azimuthal rotation through an azimuthal angle to the sample about an azimuthal axis,

such that the sample can be rotated into a measurement position;

a source moveably disposed at an incident angle with respect to the sample stage and that produces source electrons directed toward the sample;

a source collimator interposed between the source and the sample stage and that:

receives the source electrons;

collimates the source electrons; and

produces incident electrons from the source electrons in response to collimating the source electrons,

the source collimator comprising an electron lens and source transmission aperture having an incident angular width from 0° to 5° and that provides incident electrons along an incident direction at incident angle providing an incident footprint of impinging electrons on sample surface at the point of common intersection with pitch axis, roll axis and azimuthal axis, with incident angle being adjustable from 0° to 5° relative to the plane through the pitch axis and the roll axis and incident footprint having length and width controllable via source collimator;

a detection collimator disposed at a detection angle with respect to the sample stage and that:

receives reflected electrons that are reflected by the sample and produced from the incident electrons;

collimates the reflected electrons; and

produces collimated reflected electrons from the reflected electrons in response to collimating the reflected electrons,

the detection collimator comprising a detection transmission aperture having a detection angular width from 0.002° to 5°, and the detection angle being adjustable from 0° to 5° relative to a plane through the pitch axis and the roll axis; and

an electron detector that receives the collimated reflected electrons, the electron detector being disposed at the detection angle and with the detection collimator interposed between the sample stage and the electron detector.

2. The electron reflectometer of claim **1**, further comprising an energy filter that:

receives the collimated reflected electrons from the detection collimator;

filters the collimated reflected electrons based on an energy of the collimated reflected electrons; and

communicates the collimated reflected electrons to the electron detector based on the energy of the collimated reflected electrons.

3. The electron reflectometer of claim **1**, further comprising an energy filter that:

receives the reflected electrons from the sample;

filters the reflected electrons based on an energy of the reflected electrons; and

communicates the reflected electrons to the detection collimator based on the energy of the reflected electrons.

4. The electron reflectometer of claim **1**, further comprising an analyzer that:

receives a detector signal from the electron detector;

analyzes the detector signal; and

determines a surface morphology of the sample.

5. The electron reflectometer of claim **1**, further comprising the sample.

6. The electron reflectometer of claim **1**, wherein the reflected electrons and the collimated reflected electrons independently comprise:

elastically scatted electrons, inelastically scatted electrons, specularly reflected electrons, non-specularly reflected electrons, diffracted electrons, secondary electons, or a combination comprising at least one of the foregoing types of reflected electrons.

7. A process for performing shape metrology of a sample with the electron reflectometer of claim **1**, the process comprising:

producing the source electrons;

receiving, by the source collimator, the source electrons from the source;

collimating, by the source collimator, the source electrons;

producing, by the source collimator, the incident electrons from the source electrons;

subjecting the sample disposed on the sample stage to the incident electrons from the source collimator with electrons impinging upon the sample surface within an incident footprint that has length and width controllable by source collimator;

producing reflected electrons from the incident electrons in response to receipt of the incident electrons by the sample;

collimating, by the detection collimator, the reflected electrons;

producing, by the detection collimator, the collimated reflected electrons; and

receiving, by the electron detector, the collimated reflected electrons from the detection collimator to perform shape metrology of the sample.

8. The process of claim **7**, further comprising disposing the sample on the sample stage.

9. The process of claim **8**, further comprising disposing the sample with sample surface perpendicular to azimuthal axis and coincident with point of common intersection of all three rotation axes: pitch axis, roll axis, and azimuthal axis.

10. The process of claim **8**, further comprising rotating the sample into a position to be analyzed.

11. The process of claim **10**, wherein rotating the sample comprises:

performing a pitch rotation through a pitch angle about a pitch axis;

performing a roll rotation through a roll angle about a roll axis;

performing an azimuthal rotation through an azimuthal angle about an azimuthal axis; or

a combination comprising at least one of the foregoing rotations.

12. The process of claim **11**, further comprising sequentially or continuously scanning through at least one rotation selected from the pitch rotation, the roll rotation, and the azimuthal rotation while keeping the fixed at optimum values a rotation selected from the pitch rotation, the roll rotation, and the azimuthal rotation to enhance sensitivity to geometric a feature that includes top-rounding, undercut, sidewall angle, or roughness.

13. The process of claim **7**, further comprising rotating the incident direction through the incident angle.

14. The process of claim **7**, further comprising rotating the detection direction through the detection angle.

15. The process of claim **7**, further comprising:

receiving, by an energy filter, the collimated reflected electrons from the detection collimator;

filtering the collimated reflected electrons based on an energy of the collimated reflected electrons; and

communicating the collimated reflected electrons to the electron detector from the energy filter based on the energy of the collimated reflected electrons.

16. The process of claim **7**, further comprising:

receiving, by an energy filter, the reflected electrons from the sample;

filtering the reflected electrons based on an energy of the reflected electrons; and

communicating the reflected electrons to the detection collimator from the energy filter based on the energy of the reflected electrons.

17. The process of claim **7**, further comprising:

receiving, by an analyzer, a detector signal from the electron detector;

analyzing the detector signal; and

determining a surface morphology of the sample based on the detector signal.

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