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(54) **MUELLER MATRIX ELLIPSOMETER**

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(57)   **ABSTRACT**

Embodiments of the present invention relate to an ellipsometer that includes a combination of a plurality of reflective devices to measure a Mueller matrix reflectance of a material in the VUV and EUV region. Ellipsometer in accordance with embodiments of the present invention relate to an ellipsometer that includes a multi-mirror polarization state generator combined with a multi-mirror polarization state analyzer and a detector to realize a Mueller matrix ellipsometer. Embodiments of the present invention utilize two rotating assemblies with each assembly including multiple mirrors that combine to act as amplitude and phase retarders.

Figure 1

Figure 2

300

300c   300b

104d   104c   104b

104e   104a

300d   300a
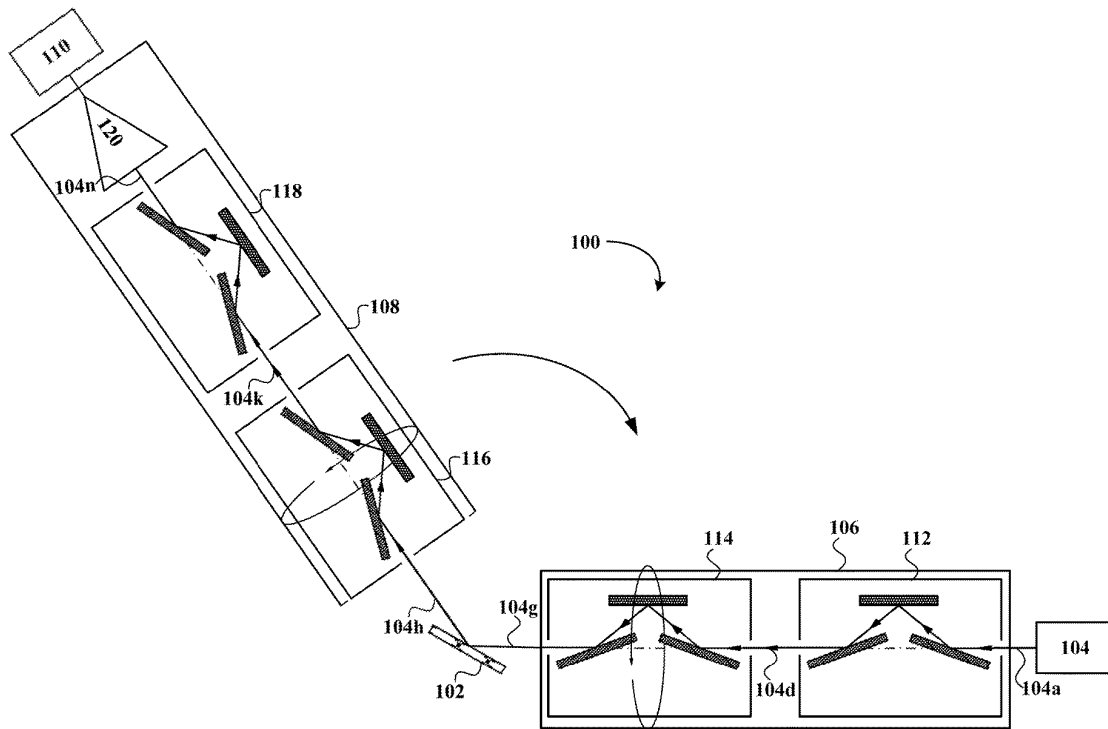
Figure 3

Figure 4

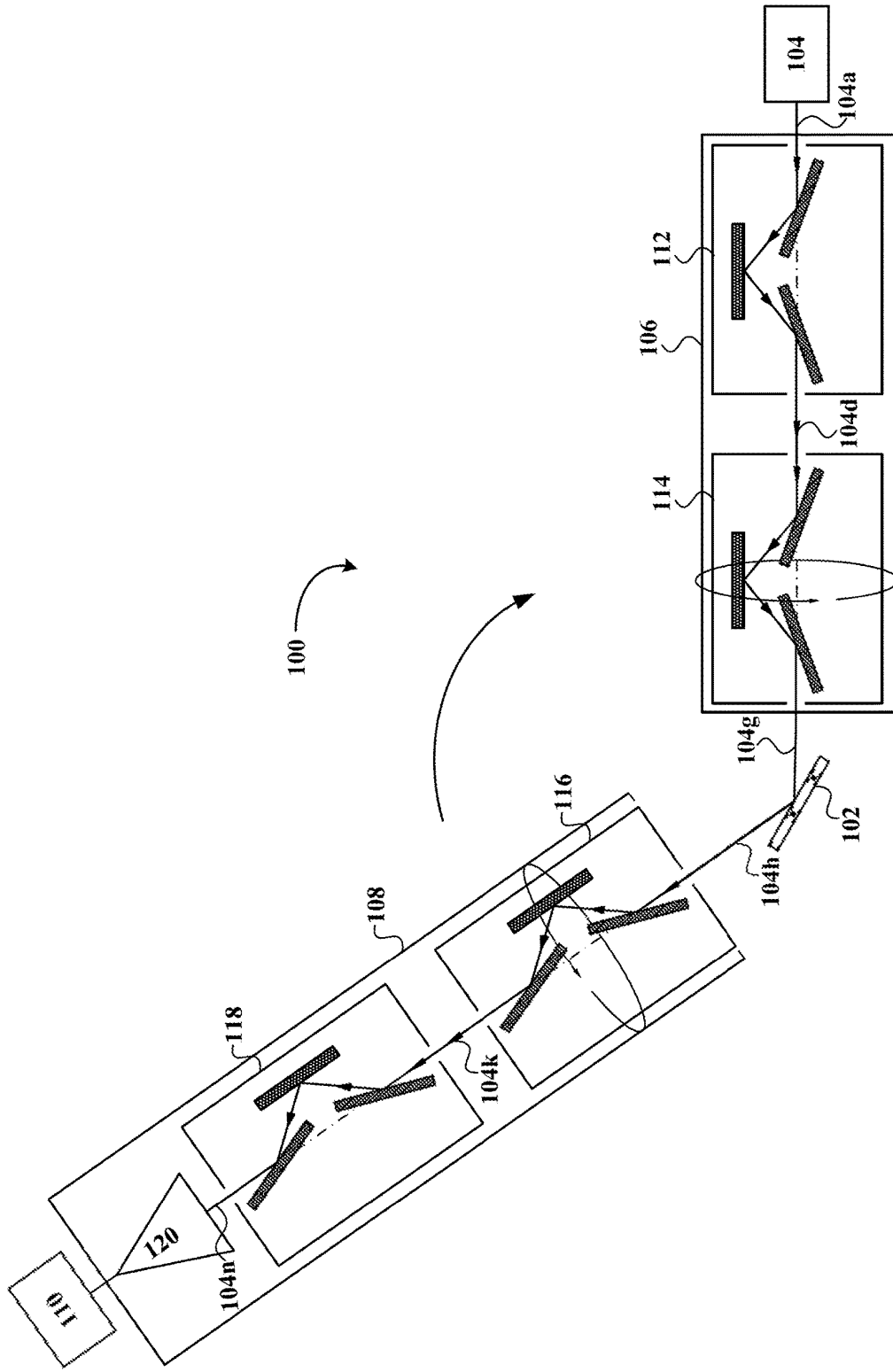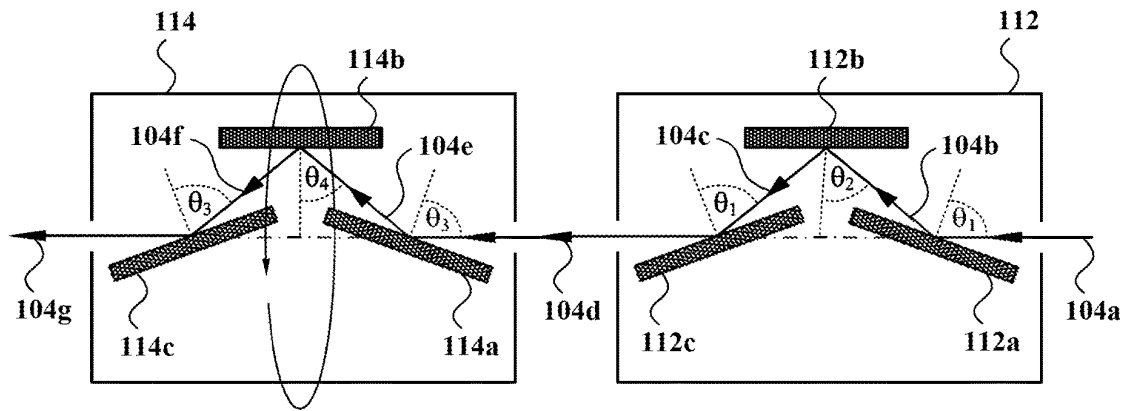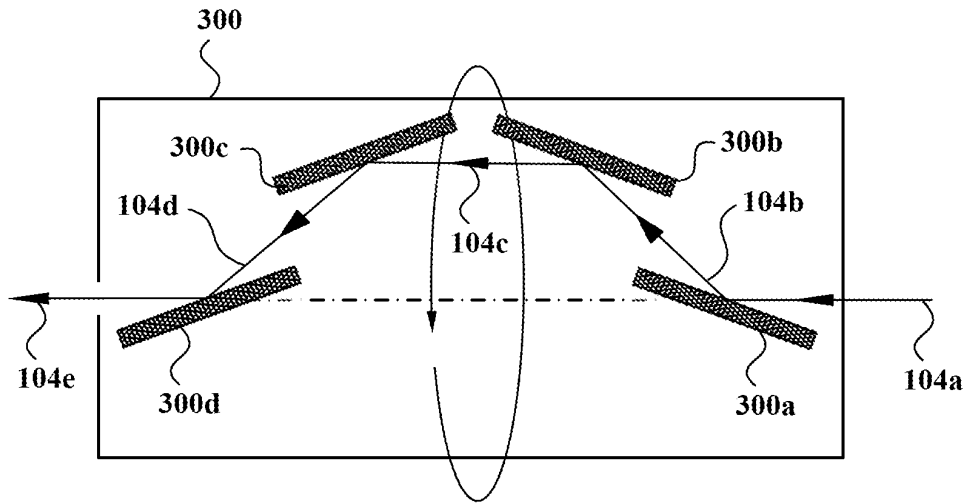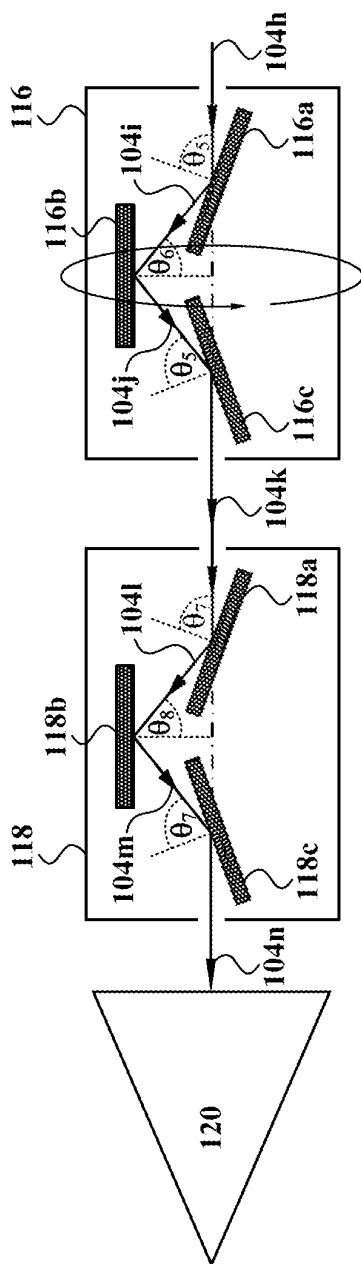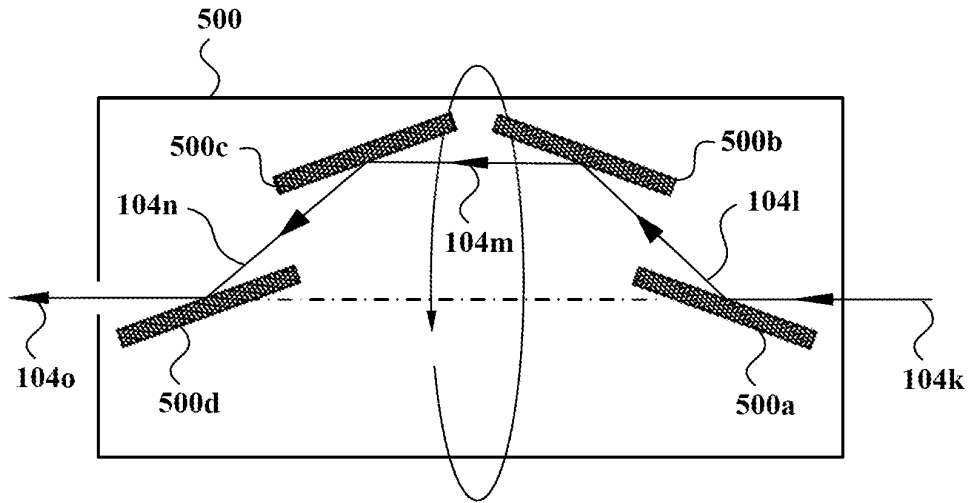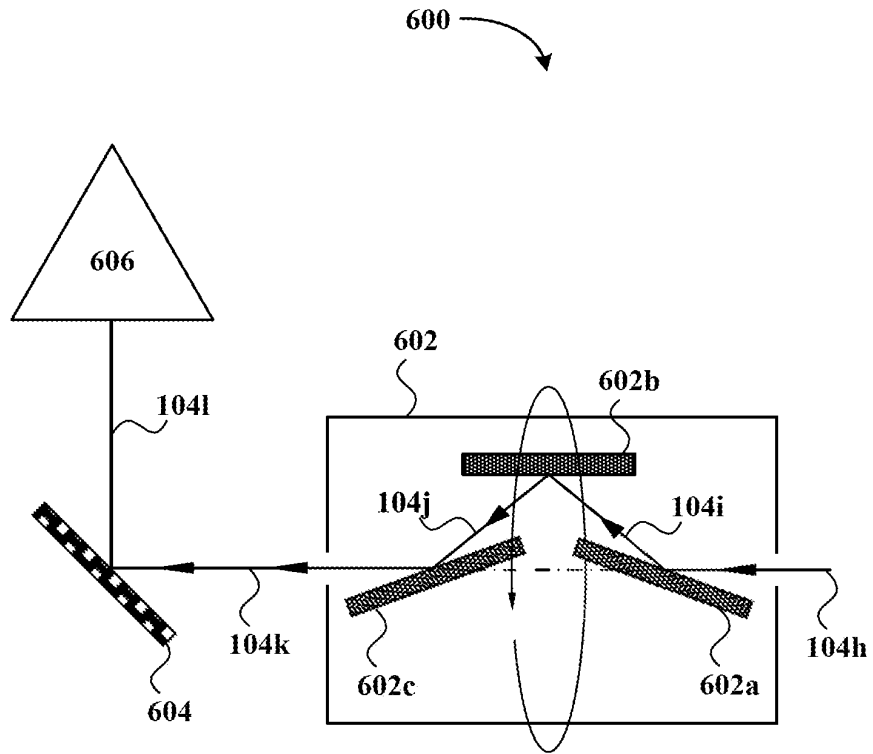Figure 5

600

602

602b

606

104l
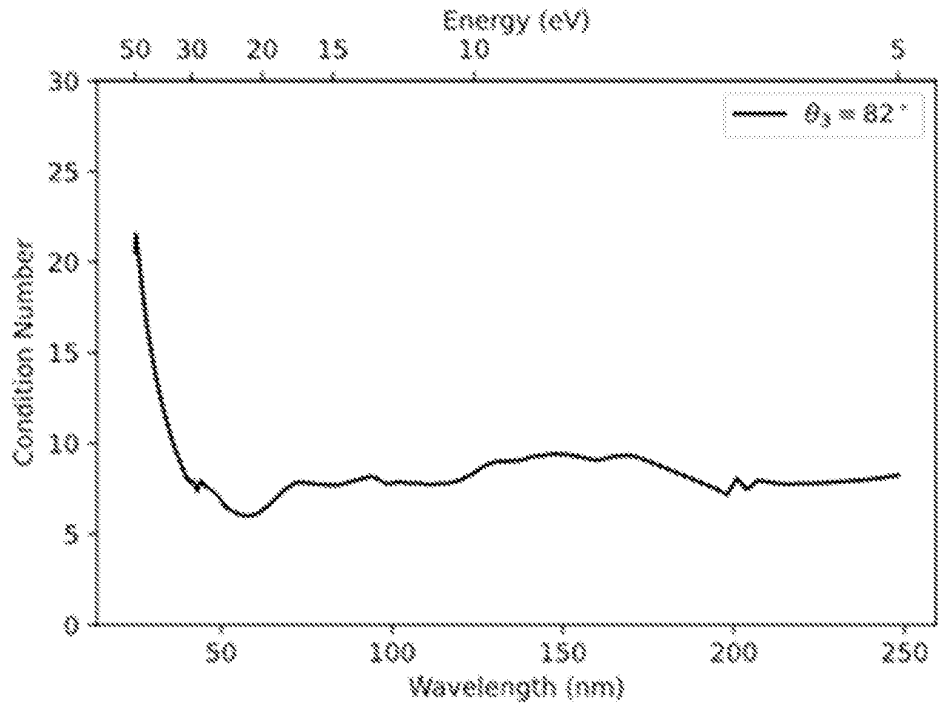
104j   104i

104k

602c   602a
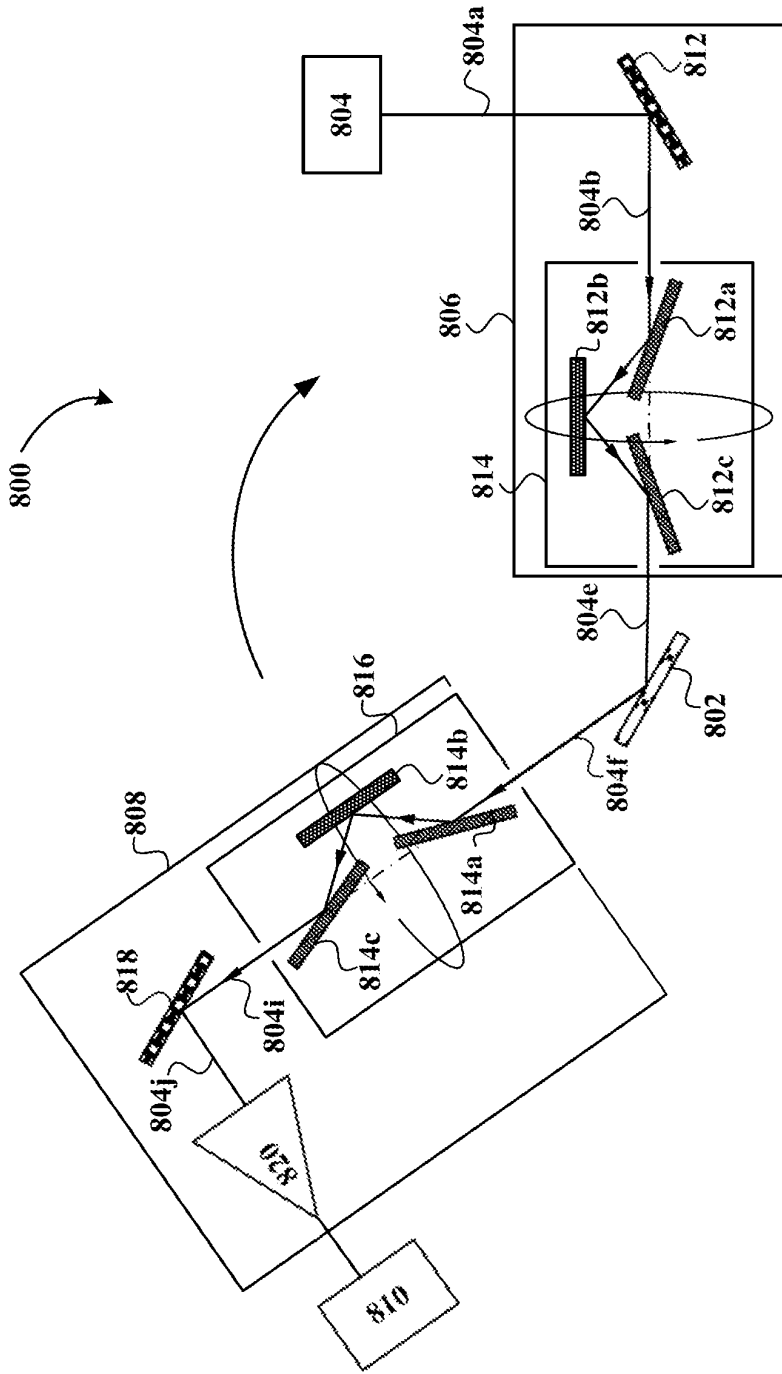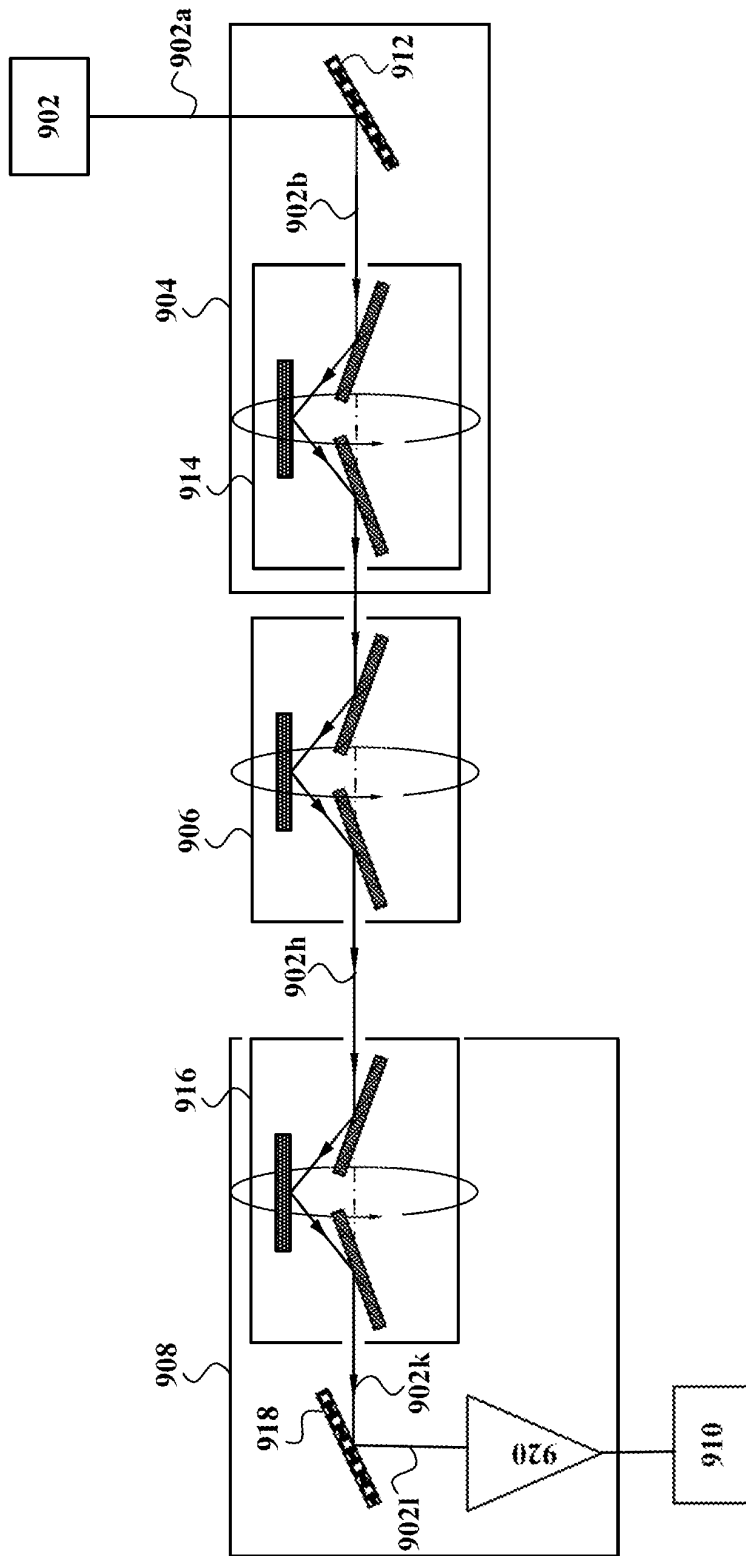
604

104h

Figure 6

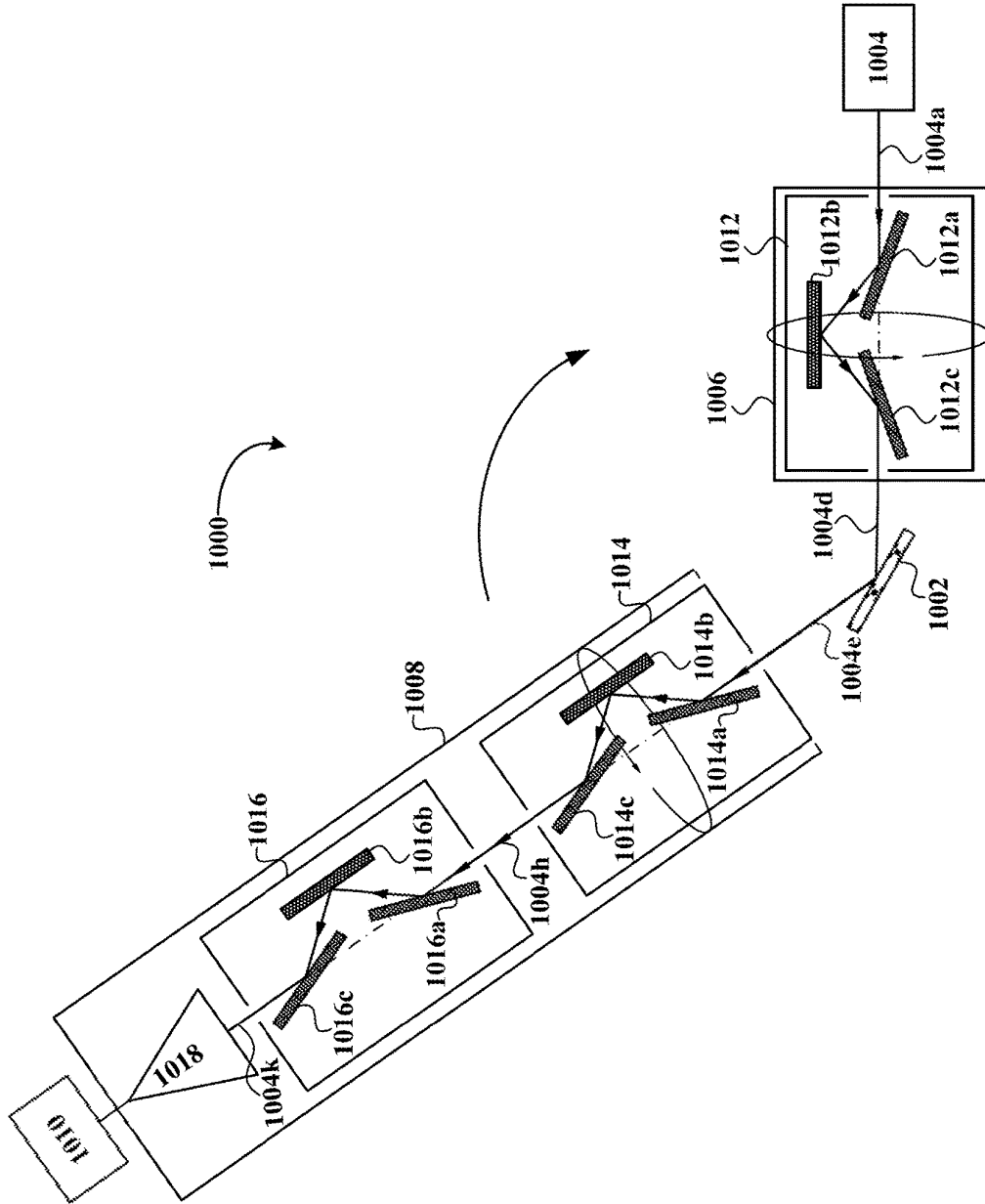Figure 7

Figure 8

Figure 9

Figure 10

MUELLER MATRIX ELLIPSOMETER

CROSS-REFERENCE TO RELATED APPLICATION

[0001] This application claims the benefit of priority from U.S. Provisional Patent Application Ser. No. 63/358,717, filed on Jul. 6, 2022, the disclosure of which is incorporated herein by reference in its entirety.

STATEMENT REGARDING FEDERAL RIGHTS

[0002] The invention described herein 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 United States Government has certain rights in the invention.

FIELD OF THE INVENTION

[0003] The present invention relates generally to optical analyzers, and more particularly to a Mueller matrix ellipsometer.

BACKGROUND OF THE INVENTION

[0004] Spectroscopic ellipsometry is a measurement technique often used for measuring the dielectric function of materials, the thicknesses and dielectric functions of films, and/or the dimensions and dielectric functions of complex periodic structures. This technique measures the change in polarization state of optical radiation upon reflection from the sample as a function of the wavelength of the optical radiation, and dielectric functions and dimensions are inferred from the measurement data through inverse electromagnetic modeling. Spectroscopic ellipsometry can also be used to determine the dimensions and dielectric functions in a period structure, and such applications are often referred to as scatterometry or optical critical dimension metrology.

[0005] Ellipsometry requires control of the polarization of the incident radiation and analysis of the polarization of the reflected radiation. While measurements from isotropic materials and thin films only require a subspace of incident and analyzed polarization states, measurements from anisotropic materials and structures benefit from a full spanning of incident and analyzed polarization states, in what is referred to as Mueller matrix ellipsometry. Typical polarization control and/or analysis is performed using optical devices that act either as polarizers or as phase retarders. A preferred polarizer exhibits a diattenuation, such that one polarization is transmitted or reflected with little attenuation while the orthogonal polarization is attenuated. A preferred phase retarder, often referred to as a wave plate or a compensator, is a device that alters the phase of one polarization with respect to its orthogonal polarization but without changing its amplitude. These devices can be combined to perform polarization control and analysis. If a source generating unpolarized radiation is followed first by a fixed polarizer and then by a rotating phase retarder, the exiting radiation will include polarization spanning all degrees of freedom. Similarly, in reverse, complete polarization analysis of radiation can be performed by passing the radiation first through a rotating phase retarder then through a fixed polarizer before striking a detector. A complete analysis of the reflection properties of a sample (what is known as the

Mueller matrix) can be achieved using a complete polarization state generator together with a complete polarization state analyzer.

[0006] Ellipsometers have been constructed for operation in the terahertz, infrared, visible, and ultraviolet spectral regions, having a minimum wavelength of about 140 nm. Extending such devices into the vacuum ultraviolet (VUV) and extreme ultraviolet (EUV) regions of the electromagnetic spectrum have been impeded because nearly all materials are opaque in these regions. Therefore, these devices will need to rely upon reflection from surfaces instead of transmission through materials. While a reasonable polarizer may be possible for this purpose, constructing an ideal phase retarder is difficult because reflection from a surface generally yields both diattenuation and retardance of the two natural polarization states with respect to each other. This difficulty increases with the need for an ideal phase retarder over a broad spectral range.

[0007] Accordingly, there is a need for an ellipsometer having polarization state analyzer and polarization state generator capable of operating in the VUV and EUV regions of the electromagnetic spectrum to determine a Mueller matrix reflectance of a material.

SUMMARY OF THE INVENTION

[0008] Embodiments of the present invention relate to an ellipsometer that includes a combination of a plurality of reflective devices to measure a Mueller matrix reflectance of a material in the VUV and EUV region. Embodiments of the present invention relate to an ellipsometer that includes a multi-mirror polarization state generator combined with a multi-mirror polarization state analyzer and a detector to realize a Mueller matrix ellipsometer.

[0009] Embodiments of the present invention also relate to an ellipsometer for investigating a sample, said ellipsometer including a radiation source for generating a non-polarized radiation beam; a polarization state generator including a first polarizer comprising a first plurality of mirrors positioned to modify the non-polarized radiation beam to a first polarized radiation beam, wherein an optical axis of the first polarized radiation beam is substantially aligned with an optical axis of the non-polarized radiation beam; and a first rotating compensator comprising a second plurality of mirrors for altering the first polarized radiation beam to a second polarized radiation beam having a first phase retardance, wherein an optical axis of the second polarized radiation beam is substantially aligned with the optical axis of the first polarized radiation beam; a sample holder for positioning a first surface of the sample to receive the second polarized radiation beam from the first rotating compensator, wherein the first surface of the sample reflects a third polarized radiation beam; a polarization state analyzer including a second rotating compensator comprising a third plurality of mirrors for altering the third polarized radiation beam to a fourth polarized radiation beam having a second phase retardance, wherein an optical axis of the fourth polarized radiation beam is substantially aligned with the optical axis of the third polarized radiation beam; and a second polarizer comprising a fourth plurality of mirrors for modifying the fourth polarized radiation beam to a fifth polarized radiation beam, wherein an optical axis of the fifth polarized radiation beam is substantially aligned with an optical axis of the fourth polarized radiation beam; a detector for measuring a plurality of first signals for a plurality of first rotation angles

of the first rotating compensator and a plurality of second signals for a plurality of second rotation angles of the second rotating compensator; and a processor for determining a Mueller matrix from the plurality of the first rotation angles of the first rotating compensator and the plurality of the second rotation angles of the second rotating compensator. More particularly, at least one of the first polarizer, the second polarizer, the first compensator and the second compensator include three mirrors.

[0010] In one embodiment, the non-polarized radiation beam has a wavelength in vacuum ultraviolet region of an electromagnetic spectrum. In another embodiment, the non-polarized radiation beam has a wavelength in extreme ultraviolet region of an electromagnetic spectrum.

[0011] In one aspect of the present invention, the first plurality of mirrors includes: a first mirror positioned to reflect the non-polarized radiation beam incident on the first mirror as a first reflected radiation beam; a second mirror positioned to reflect the first reflected radiation beam incident on the second mirror as a second reflected radiation beam; and a third mirror positioned to reflect the second reflected radiation beam incident on the third mirror as the first polarized radiation beam; the second plurality of mirrors include: a fourth mirror positioned to reflect the first polarized radiation beam incident on the fourth mirror as a third reflected radiation beam; a fifth mirror positioned to reflect the third reflected radiation beam incident on the fifth mirror as a fourth reflected radiation beam; and a sixth mirror positioned to reflect the fourth reflected radiation beam incident on the sixth mirror as the second polarized radiation beam having the first phase retardance; the third plurality of mirrors includes: a seventh mirror positioned to reflect the third polarized radiation beam incident on the seventh mirror as fifth reflected radiation beam; an eighth mirror positioned to reflect the fifth reflected radiation beam incident on the eighth mirror as a sixth reflected radiation beam; and a ninth mirror positioned to reflect the sixth reflected radiation beam incident on the ninth mirror as the fourth polarized radiation beam having the second phase retardance; and the fourth plurality of mirrors includes: a tenth mirror positioned to reflect the fourth polarized radiation beam incident on the tenth mirror as a seventh reflected radiation beam; an eleventh mirror positioned to reflect the seventh reflected radiation beam incident on the eleventh mirror as an eighth reflected radiation beam; and a twelfth mirror positioned to reflect the eighth reflected radiation beam incident on the twelfth mirror as the fourth polarized radiation beam.

[0012] In one embodiment of the present invention, the first plurality of mirrors further includes a thirteenth mirror positioned to receive one of the non-polarized radiation beam, the first reflected radiation beam and the second reflected radiation beam, wherein the first, the second, the third and the thirteenth mirrors modify the non-polarized radiation beam to the first polarized radiation beam. In a second embodiment of the present invention, the second plurality of mirrors further comprises a fourteenth mirror positioned to receive one of the first polarized radiation beam, the third reflected radiation beam and the fourth reflected radiation beam, wherein the fourth, the fifth, the sixth and the fourteenth mirrors alter the first polarized radiation beam to the second polarized radiation beam having the first phase retardance. In a third embodiment of the present invention, the third plurality of mirrors further

comprises a fourteenth mirror positioned to receive one of the third polarized radiation beam, the fifth reflected radiation beam and the sixth reflected radiation beam, wherein the seventh, the eighth, the ninth and the fourteenth mirrors alter the third polarized radiation beam to the fourth polarized radiation beam having the second phase retardance. In a fourth embodiment of the present invention, the fourth plurality of mirrors further comprises a fourteenth mirror positioned to receive one of the fourth polarized radiation beam, the seventh reflected radiation beam and the eighth reflected radiation beam, wherein the tenth, the eleventh, the twelfth and the fourteenth mirrors modify the fourth polarized radiation beam to the fifth polarized radiation beam.

[0013] In one aspect of the present invention, the first rotating compensator is rotated about an axis substantially aligned with the optical axes of the first and the second polarized radiation beams, and wherein the second compensator is rotated about an axis substantially aligned with the optical axes of the third and the fourth polarized radiation beams.

[0014] In some aspects of the present invention, the polarization state analyzer is rotated about an axis passing through a location the second polarized radiation beam is received on the first surface of the sample positioned on the sample holder, wherein the sample holder rotates the sample about the axis passing through the location the second polarized radiation beam is received on the first surface of the sample positioned on the sample holder, wherein the rotation of the sample is about one-half of the rotation of the polarization state analyzer, and wherein the rotating the polarization state analyzer adjusts an angle of incidence of the second polarized radiation beam on the first surface of the sample positioned on the sample holder and an angle of reflection of the third polarized radiation beam. In other aspects of the present invention, the sample holder rotates the sample in an azimuthal direction about an axis normal to the first surface of the sample.

[0015] Embodiments of the present invention also relate to an ellipsometer for investigating a sample, said ellipsometer including a radiation source for generating a non-polarized radiation beam having a wavelength from about 10 nm to about 240 nm; a first polarizer for modifying the non-polarized radiation beam to a first polarized radiation beam, wherein an optical axis of the first polarized radiation beam is substantially aligned with an optical axis of the non-polarized radiation beam, wherein the first polarizer includes: a first mirror positioned to reflect the non-polarized radiation beam incident on the first mirror as a first reflected radiation beam; a second mirror positioned to reflect the first reflected radiation beam incident on the second mirror as a second reflected radiation beam; and a third mirror positioned to reflect the second reflected radiation beam incident on the third mirror as the first polarized radiation beam; a first rotating compensator for altering the first polarized radiation beam to a second polarized radiation beam having a first phase retardance, wherein an optical axis of the second polarized radiation beam is substantially aligned with the optical axis of the first polarized radiation beam, wherein the first compensator is rotated about an axis substantially aligned with the optical axes of the first and the second polarized radiation beams, wherein the first rotating compensator includes: a fourth mirror positioned to reflect the first polarized radiation beam incident on the fourth mirror as a third reflected radiation beam, wherein the third

reflected radiation beam comprises a second phase retardance; a fifth mirror positioned to reflect the third reflected radiation beam incident on the fifth mirror as a fourth reflected radiation beam, wherein the fourth reflected radiation beam comprises a third phase retardance; and a sixth mirror positioned to reflect the fourth reflected radiation beam incident on the sixth mirror as the second polarized radiation beam having the first phase retardance; a sample holder for positioning a first surface of the sample to receive the second polarized radiation beam from the first rotating compensator, wherein the first surface of the sample reflects a third polarized radiation beam; a second rotating compensator for altering the third polarized radiation beam to a fourth polarized radiation beam having a fourth phase retardance, wherein an optical axis of the fourth polarized radiation beam is substantially aligned with the optical axis of the third polarized radiation beam, wherein the second compensator is rotated about an axis substantially aligned with the optical axes of the third and the fourth polarized radiation beams, wherein the second compensator includes: a seventh mirror positioned to reflect the third polarized radiation beam incident on the seventh mirror as a fifth reflected radiation beam, wherein the fifth reflected radiation beam comprises a fifth phase retardance; an eighth mirror positioned to reflect the fifth reflected radiation beam incident on the eighth mirror as a sixth reflected radiation beam, wherein the sixth reflected beam comprises a sixth phase retardance; and a ninth mirror positioned to reflect the sixth reflected radiation beam incident on the ninth mirror as the fourth polarized radiation beam having the fourth phase retardance; a second polarizer for modifying the fourth polarized radiation beam to a fifth polarized radiation beam, wherein an optical axis of the fifth polarized radiation beam is substantially aligned with an optical axis of the fourth polarized radiation beam, wherein the second polarizer includes: a tenth mirror positioned to reflect the fourth polarized radiation beam incident on the tenth mirror as a seventh reflected radiation beam; an eleventh mirror positioned to reflect the seventh reflected radiation beam incident on the eleventh mirror as an eighth reflected radiation beam; and a twelfth mirror positioned to reflect the eighth reflected radiation beam incident on the twelfth mirror as the fifth polarized radiation beam; a detector for measuring a plurality of first signals for a plurality of first rotation angles of the first rotating compensator and a plurality of second signals for a plurality of second rotation angles of the second rotating compensator; and a processor for determining a Mueller matrix from the plurality of the first rotation angles of the first rotating compensator and the plurality of the second rotation angles of the second rotating compensator.

[0016] In one embodiment of the present invention, the first polarizer further comprises a thirteenth mirror positioned to receive one of the non-polarized radiation beam, the first reflected radiation beam and the second reflected radiation beam, and wherein the first, the second, the third and the thirteenth mirrors are positioned to modify the non-polarized radiation beam to the first polarized radiation beam. In another embodiment of the present invention, the second polarizer further comprises a thirteenth mirror positioned to receive one of the fourth polarized radiation beam, the seventh reflected radiation beam and the eighth reflected radiation beam, and wherein the tenth, the eleventh, the twelfth and the thirteenth mirrors are positioned to modify the fourth polarized radiation beam to the fifth polarized

radiation beam. In yet another embodiment of the present invention, the first polarizer further comprises a thirteenth mirror positioned to receive a ninth reflected radiation beam from the third mirror, and wherein the thirteenth mirror is positioned to reflect the ninth reflected radiation beam incident on the thirteenth mirror as the first polarized radiation beam, and wherein the second polarizer further comprises a fourteenth mirror positioned to receive a tenth reflected radiation beam from the twelfth mirror, and wherein the fourteenth mirror is positioned to reflect the tenth reflected radiation beam incident on the fourteenth mirror as the fifth polarized radiation beam.

[0017] Another embodiment of the present invention relates to an ellipsometer for investigating a sample, said ellipsometer including a radiation source for generating a non-polarized radiation beam; a polarization state generator for modifying the non-polarized radiation beam to a first polarized radiation beam having a first phase retardance, wherein the polarization state generator includes: a first mirror positioned to reflect the non-polarized radiation beam incident on the first mirror as a first reflected radiation beam; a second mirror positioned to reflect the first reflected radiation beam incident on the second mirror as a second reflected radiation beam; a third mirror positioned to reflect the second reflected radiation beam incident on the second mirror as a third reflected radiation beam; a fourth mirror positioned to reflect the third reflected radiation beam incident on the third mirror as a fourth reflected radiation beam; and a first rotating compensator for altering the fourth reflected radiation beam to the first polarized radiation beam having the first phase retardance, wherein an optical axis of the first polarized radiation beam is substantially aligned with the optical axis of the non-polarized radiation beam, wherein the first compensator is rotated about an axis substantially aligned with the optical axis of the first polarized radiation beam; a sample holder for positioning a first surface of the sample to receive the first polarized radiation beam from the polarization state generator, wherein the first surface of the sample reflects a second polarized radiation; a polarization analyzer including: a second rotating compensator for altering the second polarized radiation beam to a third polarized radiation beam having a second phase retardance, wherein an optical axis of the third polarized radiation beam is substantially aligned with the optical axis of the second polarized radiation beam, wherein the compensator is rotated about an axis substantially aligned with the optical axes of the second and the third polarized radiation beams; and a polarizer for modifying the third polarized radiation beam to a fourth polarized radiation beam, wherein an optical axis of the fourth polarized radiation beam is substantially aligned with an optical axis of the third polarized radiation beam; a detector for measuring a plurality of first signals for a plurality of first rotation angles of the polarization state generator and a plurality of second signals for a plurality of second rotation angles of the rotating compensator; and a processor for determining a Mueller matrix from the plurality of the first rotation angles of the polarization state generator and the plurality of the second rotation angles of the rotating compensator.

[0018] In one embodiment of the present invention, the first rotating compensator includes a fifth mirror positioned to reflect the fourth reflected radiation beam incident on the fifth mirror as a fifth reflected radiation beam, wherein the fifth reflected radiation beam comprises a third phase retar-

dance; a sixth mirror positioned to reflect the fifth reflected radiation beam incident on the sixth mirror as a sixth reflected radiation beam, wherein the fifth reflected beam comprises a fourth phase retardance; and a seventh mirror positioned to reflect the sixth reflected radiation beam incident on the seventh mirror as the first polarized radiation beam having the first phase retardance.

[0019] In one embodiment of the present invention, the second rotating compensator includes a fifth mirror positioned to reflect the second polarized radiation beam incident on the fifth mirror as a fifth reflected radiation beam, wherein the fifth reflected radiation beam comprises a third phase retardance; a sixth mirror positioned to reflect the fifth reflected radiation beam incident on the sixth mirror as a sixth reflected radiation beam, wherein the sixth reflected beam comprises a fourth phase retardance; and a seventh mirror positioned to reflect the sixth reflected radiation beam incident on the seventh mirror as the third polarized radiation beam having the second phase retardance.

[0020] In one embodiment of the present invention, the polarizer includes a fifth mirror positioned to reflect the third polarized radiation beam incident on the fifth mirror as a fifth reflected radiation beam; a sixth mirror positioned to reflect the fifth reflected radiation beam incident on the sixth mirror as a sixth reflected radiation beam; and a seventh mirror positioned to reflect the sixth reflected radiation beam incident on the seventh mirror as the fourth polarized radiation beam. In another embodiment of the present invention, the polarizer includes a fifth mirror positioned to reflect the third polarized radiation beam incident on the fifth mirror as a fifth reflected radiation beam; a sixth mirror positioned to reflect the fifth reflected radiation beam incident on the sixth mirror as a sixth reflected radiation beam; and a seventh mirror positioned to reflect the sixth reflected radiation beam incident on the seventh mirror as a seventh reflected radiation beam; and an eighth mirror positioned to receive the seventh reflected radiation beam incident on the eighth mirror as the fourth polarized radiation beam.

[0021] Embodiments of the present invention also relate to an ellipsometer for investigating a sample, said ellipsometer including a radiation source for generating a non-polarized radiation beam; a polarization state generator including: a first Brewster mirror for modifying the non-polarized radiation beam to a first polarized radiation beam, wherein the first polarized radiation beam comprises a first parallel optical component and a first orthogonal optical component; a first rotating compensator comprising a first plurality of mirrors for altering the first polarized radiation beam to a second polarized radiation beam having a first phase retardance, wherein an optical axis of the second polarized radiation beam is substantially aligned with an optical axis of the first polarized radiation beam, wherein the first rotating compensator is rotated about an axis substantially aligned with the optical axes of the first and the second polarized radiation beams; a sample holder for positioning a first surface of the sample to receive the second polarized radiation beam from the first rotating compensator, wherein the first surface of the sample reflects a third polarized radiation beam; a polarization analyzer including: a second rotating compensator comprising a second plurality of mirrors for altering the third polarized radiation beam to a fourth polarized radiation beam having a second phase retardance, wherein an optical axis of the fourth polarized radiation beam is substantially aligned with an optical axis of the third

polarized radiation beam, wherein the second compensator is rotated about an axis substantially aligned with the optical axes of the third and the fourth polarized radiation beams; and a second Brewster mirror for modifying the fourth polarized radiation beam to a fifth polarized radiation beam, wherein the fifth polarized radiation beam comprises a second parallel optical component and a second orthogonal optical component, wherein an optical axis of the fifth polarized radiation beam is substantially aligned with the optical axis of the fourth polarized radiation beam, wherein the polarization state analyzer is rotated about an axis passing through a location the second polarized radiation beam is received on the first surface of the sample positioned on the sample holder, wherein the sample holder rotates the sample about the axis passing through the location the second polarized radiation beam is received on the first surface of the sample positioned on the sample holder, wherein the rotation of the sample is about one-half of the rotation of the polarization state analyzer, and wherein the rotating the polarization state analyzer adjusts an angle of incidence of the second polarized radiation beam on the first surface of the sample positioned on the sample holder and an angle of reflection of the third polarized radiation beam; a detector for measuring a plurality of first signals for a plurality of first rotation angles of the first rotating compensator and a plurality of second signals for a plurality of second rotation angles of the second rotating compensator; and a processor for determining a Mueller matrix from the plurality of the first rotation angles of the first rotating compensator and the plurality of the second rotation angles of the second rotating compensator.

[0022] In some embodiments of the present invention, the first plurality of mirrors includes a first mirror positioned to reflect the non-polarized radiation beam incident on the first mirror as a first reflected radiation beam; a second mirror positioned to reflect the first reflected radiation beam incident on the second mirror as a second reflected radiation beam; and a third mirror positioned to reflect the second reflected radiation beam incident on the third mirror as the first polarized radiation beam having the first phase retardance. In other embodiments of the present invention, the second plurality of mirrors includes a fourth mirror positioned to reflect the first polarized radiation beam incident on the fourth mirror as a third reflected radiation beam; a fifth mirror positioned to reflect the third reflected radiation beam incident on the fifth mirror as a fourth reflected radiation beam; and a sixth mirror positioned to reflect the fourth reflected radiation beam incident on the sixth mirror as the second polarized radiation beam having the second phase retardance.

[0023] Another embodiment of the present invention relates to an ellipsometer for investigating a sample, said ellipsometer including a radiation source for generating a first polarized radiation beam having a wavelength from about 10 nm to about 240 nm in an electromagnetic spectrum; a first rotating compensator for altering the first polarized radiation beam to a second polarized radiation beam, wherein an optical axis of the second polarized radiation beam is substantially aligned with the optical axis of the first polarized radiation beam, wherein the first compensator is rotated about an axis substantially aligned with the optical axes of the first and the second polarized radiation beams, wherein the first rotating compensator comprises: a first mirror positioned to reflect the first polar-

ized radiation beam incident on the first mirror as a first reflected radiation beam, wherein the first reflected radiation beam comprises a first phase retardance; a second mirror positioned to reflect the first reflected radiation beam incident on the second mirror as a second reflected radiation beam, wherein the second reflected radiation beam comprises a second phase retardance; and a third mirror positioned to reflect the second reflected radiation beam incident on the sixth mirror as the second polarized radiation beam having a third phase retardance; a sample holder for positioning a first surface of the sample to receive the second polarized radiation beam from the first rotating compensator, wherein the first surface of the sample reflects a third polarized radiation beam; a second rotating compensator for altering the third polarized radiation beam to a fourth polarized radiation beam, wherein an optical axis of the fourth polarized radiation beam is substantially aligned with the optical axis of the third polarized radiation beam, wherein the second compensator is rotated about an axis substantially aligned with the optical axes of the third and the fourth polarized radiation beams, wherein the second compensator includes: a fourth mirror positioned to reflect the third polarized radiation beam incident on the fourth mirror as a third reflected radiation beam, wherein the third reflected radiation beam comprises a fourth phase retardance; a fifth mirror positioned to reflect the third reflected radiation beam incident on the fifth mirror as a fourth reflected radiation beam, wherein the fourth reflected beam comprises a fifth phase retardance; and a sixth mirror positioned to reflect the fourth reflected radiation beam incident on the sixth mirror as the fourth polarized radiation beam having a sixth phase retardance; a polarizer for modifying the fourth polarized radiation beam to a fifth polarized radiation beam, wherein an optical axis of the fifth polarized radiation beam is substantially aligned with an optical axis of the fourth polarized radiation beam, wherein the second polarizer includes: a seventh mirror positioned to reflect the fourth polarized radiation beam incident on the seventh mirror as a fifth reflected radiation beam; an eighth mirror positioned to reflect the fifth reflected radiation beam incident on the eighth mirror as a sixth reflected radiation beam; and a ninth mirror positioned to reflect the sixth reflected radiation beam incident on the ninth mirror as the fifth polarized radiation beam; a detector for measuring a plurality of first signals for a plurality of first rotation angles of the first rotating compensator and a plurality of second signals for a plurality of second rotation angles of the second rotating compensator; and a processor for determining a Mueller matrix from the plurality of the first rotation angles of the first rotating compensator and the plurality of the second rotation angles of the second rotating compensator. In some embodiments of the present invention, the polarizer further comprises a tenth mirror positioned to receive a seventh reflected radiation beam from the ninth mirror, and wherein the tenth mirror is positioned to reflect the seventh reflected radiation beam incident on the tenth mirror as the fifth polarized radiation beam.

[0024] In one embodiment of the present invention, the wavelength of the non-polarized radiation beam is from about 10 nm to about 30 nm. In another embodiment of the present invention, the wavelength of the non-polarized radiation beam is from about 30 nm to about 240 nm.

BRIEF DESCRIPTION OF DRAWINGS

[0025] FIG. 1 illustrates a schematic representation of an ellipsometer in accordance with embodiments of the present invention.

[0026] FIG. 2 illustrates a schematic representation of a polarization state generator as used in an ellipsometer in accordance with embodiments of the present invention.

[0027] FIG. 3 illustrates a schematic representation of an alternate polarizer or compensator as used in a polarization state generator of an ellipsometer in accordance with embodiments of the present invention.

[0028] FIG. 4 illustrates a schematic representation of a polarization state analyzer as used in an ellipsometer in accordance with embodiments of the present invention.

[0029] FIG. 5 illustrates a schematic representation of an alternate polarizer or compensator as used in a polarization state analyzer of an ellipsometer in accordance with embodiments of the present invention.

[0030] FIG. 6 illustrates a schematic representation of an alternate polarization state analyzer as used in an ellipsometer in accordance with embodiments of the present invention.

[0031] FIG. 7 illustrates an exemplary plot for calculated condition number for polarization state generator or analyzer shown in FIG. 1.

[0032] FIG. 8 illustrates a schematic representation of an alternate ellipsometer in accordance with embodiments of the present invention.

[0033] FIG. 9 illustrates a schematic representation of a calibration assembly for an ellipsometer in accordance with embodiments of the present invention.

[0034] FIG. 10 illustrates a schematic representation of an alternate ellipsometer in accordance with embodiments of the present invention.

DETAILED DESCRIPTION

[0035] While the making and using of various embodiments of the present invention are discussed in detail below, it should be appreciated that the present invention provides many applicable inventive concepts which can be embodied in a wide variety of specific contexts. The specific embodiments discussed herein are merely illustrative of specific ways to make and use the invention, and do not delimit the scope of the present invention. Reference will be made to the drawings wherein like numerals refer to like elements throughout.

[0036] Referring now to the drawings, and more particularly, to FIG. 1, there is shown an ellipsometer, generally designated 100 and schematically showing an embodiment of the present invention, for measuring a Mueller matrix reflectance of a material in the VUV and EUV region. Ellipsometer 100 for probing a sample artifact includes a sample holder 102, a radiation source 104, a polarization generator 106, a polarization state analyzer 108, and a processor 110.

[0037] Radiation source 104 emits a radiation beam 104a having divergent rays that are isotropically non-polarized and having a predetermined wavelength range of interest in the vacuum or extreme ultraviolet region of the electromagnetic spectrum. In some embodiments of the present invention, radiation source 104 emits a radiation beam 104a having divergent rays that are naturally polarized and having a predetermined wavelength range of interest in the vacuum

or extreme ultraviolet region of the electromagnetic spectrum. In one embodiment of the present invention, radiation source **104** emits radiation beam **104***a* in the vacuum ultraviolet region over a predetermined wavelength range of from about 30 nm to about 240 nm. In another embodiment of the present invention, radiation source **104** emits radiation beam **104***a* in the extreme ultraviolet region over a predetermined wavelength range of from about 10 nm to about 30 nm.

[0038] Radiation beam **104***a* from radiation source **104** is transmitted to polarization state generator **106**, which imparts a known polarization state to radiation beam **104***a*. Polarization state generator **106** includes a polarizer **112** and a rotating compensator **114**. In one embodiment of the present invention, polarizer **112** includes mirrors **112***a*, **112***b*, and **112***c*, as shown in FIG. **2**, positioned to receive radiation beam **104***a* from radiation source **104** and change non-polarized radiation beam **104***a* into linearly polarized radiation beam **104***d* by diattenuation of non-polarized radiation beam **104***a*. Diattenuation of non-polarized radiation beam **104***a* is performed by taking advantage of a difference in reflectance between s-polarized radiation beam and p-polarized radiation beam and splitting the polarized light into two mutually orthogonal components that are attenuated at different rates. Mirrors **112***a-c* can be made from silicon, gold, platinum, and the like. Ellipsometer **100** operating at the shorter wavelengths, such as from about 10 nm to about 30 nm, may include mirrors **112***a-c* having multilayer stacks applied to optimize the reflectance and phase change. Mirrors **112***a-c* are rigidly arranged in a housing such that the optical axis of incoming radiation beam **104***a* received by polarizer **112** aligns with the optical axis of radiation beam **104***d* exiting polarizer **112**. Mirror **112***a* is configured such that radiation beam **104***a* is incident upon mirror **112***a* at an incident angle θ_1. Mirror **112***a* is configured to reflect incident radiation beam **104***a* such that radiation beam **104***b* reflected from mirror **112***a* is incident upon mirror **112***b* at an incident angle $\theta_2 = 2\theta_1 - 90°$. Mirror **112***b* is configured to reflect incident radiation beam **104***b* such that radiation beam **104***c* reflected from mirror **112***b* is incident on mirror **112***c* at the incident angle θ_1. In one embodiment of the present invention, θ_1 is about 80 deg. and θ_2 is about 70 deg. Mirror **112***c* is configured to reflect incident radiation beam **104***c* such that radiation beam **104***d* reflected from mirror **112***c* exits polarizer **112** as radiation beam **104***d* along an optical axis that aligns with the optical axis of radiation beam **104***a*.

[0039] Any number of mirrors can be used in polarizer **112** such that the optical axis of an incoming radiation beam and that of an outgoing radiation beam are aligned and unchanged. FIG. **3** illustrates an alternate polarizer **300** as used in an ellipsometer in accordance with an embodiment of the present invention. Polarizer **300** includes mirrors **300***a*, **300***b*, **300***c*, and **300***d* positioned to receive radiation beam **104***a* from radiation source **104** and change non-polarized radiation beam **104***a* into linearly polarized radiation beam **104***e* by taking advantage of a difference in reflectance and phase between s-polarized radiation beam and p-polarized radiation beam. Mirrors **300***a-d* are rigidly arranged in a housing such that the optical axis of incoming radiation beam **104***a* received by polarizer **300** aligns with the optical axis of radiation beam **104***e* exiting polarizer **300**. Mirror **300***a* is configured such that radiation beam **104***a* is incident upon mirror **300***a* at an incident angle θ_1. Mirror

300*a* is configured to reflect incident radiation beam **104***a* such that radiation beam **104***b* reflected from mirror **300***a* is incident upon mirror **300***b*. Mirror **300***b* is configured to reflect incident radiation beam **104***b* such that radiation beam **104***c* reflected from mirror **300***b* is incident on mirror **300***c*. Mirror **300***c* is configured to reflect incident radiation beam **104***c* such that radiation beam **104***d* reflected from mirror **300***c* is incident on mirror **300***d*. Mirror **300***d* is configured to reflect incident radiation beam **104***d* such that radiation beam **104***e* reflected from mirror **300***c* exits polarizer **300** as radiation beam **104***e* along an optical axis that aligns with the optical axis of radiation beam **104***a*.

[0040] Referring back to FIGS. **1** and **2**, compensator **114** receives radiation beam **104***d* exiting polarizer **112**. Compensator **114** includes mirrors **114***a*, **114***b*, and **114***c*, as shown in FIG. **2**, positioned to receive radiation beam **104***d* exiting polarizer **112** and introduces a relative phase delay (phase retardation) between a pair of mutually orthogonal polarized optical beam components of radiation beam **104***d*. Mirrors **114***a-c* can be made from silicon, gold, platinum, and the like. Ellipsometer **100** operating at the shorter wavelengths, such as from about 10 nm to about 30 nm, may include mirrors **114***a-c* having multilayer stacks applied to optimize the reflectance and phase change. Mirrors **114***a-c* are rigidly arranged in a housing such that the optical axis of incoming radiation beam **104***d* received from polarizer **112** aligns with the optical axis of radiation beam **104***g* exiting compensator **114**. Mirror **114***a* is configured such that radiation beam **104***d* is incident upon mirror **114***a* at an incident angle θ_3. Mirror **114***a* is configured to reflect incident radiation beam **104***d* such that radiation beam **104***e* reflected from mirror **114***a* is incident upon mirror **114***b* at an incident angle $\theta_4 = 2\theta_3 - 90°$. Mirror **114***b* is configured to reflect incident radiation beam **104***e* such that radiation beam **104***f* reflected from mirror **114***b* is incident on mirror **114***c* at the incident angle θ_3. In some embodiments of the present invention, the incident angles θ_3 and θ_4 for mirrors **114***a-c* are grazing angles. In an exemplary embodiment of the present invention, θ_1 is from about 75 deg. to about 85 deg., and θ_2 is from about 60 deg. to about 80 deg. Mirror **114***c* is configured to reflect incident radiation beam **104***f* such that radiation beam **104***g* reflected from mirror **114***c* exits compensator **114** as radiation beam **104***g* along an optical axis that aligns with the optical axes of radiation beams **104***a* and **104***d*. Any number of mirrors can be used in compensator **114** such that the optical axis of an incoming radiation beam and that of an outgoing radiation beam are aligned and unchanged. In an alternate embodiment of the present invention, compensator **114** includes four mirrors arranged in a manner as shown in FIG. **3**. A drive mechanism (not shown) can be used to rotate compensator **114** about an axis that substantially aligns with the optical axes of radiation beams **104***a*, **104***d* and **104***g*. As compensator **114** rotates, the polarization state of radiation beam **104***g* modulates along all three degrees of freedom necessary to act as a complete polarization state generator.

[0041] Radiation beam **104***g* exiting compensator **114** is directed to sample artifact positioned on sample holder **102**, as shown in FIG. **1**. Sample holder **102** is positioned such that radiation beam **104***g* exiting compensator **114** is incident on a surface of sample artifact. Sample holder **102** can be rotated such that radiation beam **104***g* is incident on a front face of the sample artifact at a predetermined incident angle. In one embodiment, sample holder **102** can be rotated

azimuthally about its surface normal. Radiation beam **104***g* incident on the front face of a sample artifact is reflected as radiation beam **104***h* into polarization state analyzer **108**.

[0042] Polarization state analyzer **108** includes a compensator **116**, a polarizer **118** and a detector **120**, as shown in FIGS. **1** and **4**. Polarization state analyzer **108** rotates about an axis passing through the location where radiation beam **114***g* strikes the front surface of the sample artifact positioned on sample holder **102** such that the angle of incidence of radiation beam **104***g* on a front face of the sample artifact varies with the rotation of polarization state analyzer **108**. In one embodiment, sample holder **102** is rotated about an axis that aligns with the axis polarization state analyzer **108** rotates about the front surface of the sample artifact positioned on sample holder **102** and sample holder **102** is rotated about half as fast as polarization state analyzer **108**. In another embodiment, sample holder **102** is rotated in an azimuthal direction about its surface normal. In some embodiments, sample holder **102** is tilted about an axis parallel to its surface. Compensator **116** includes mirrors **116***a*, **116***b*, and **116***c*, as shown in FIG. **4**, positioned to receive radiation beam **104***h* reflected from the front surface of a sample artifact positioned on sample holder **102** and introduces a relative phase delay between a pair of mutually orthogonal polarized optical beam components of radiation beam **104***i*. Mirrors **116***a-c* can be made from silicon, gold, platinum, and the like. Ellipsometer **100** operating at the shorter wavelengths, such as from about 10 nm to about 30 nm, may include mirrors **116***a-c* having multilayer stacks applied to optimize the reflectance and phase change. Mirrors **116***a-c* are rigidly arranged in a housing such that the optical axis of incoming radiation beam **104***h* reflected from the sample artifact front surface aligns with the optical axis of radiation beam **104***k* exiting compensator **116**. Mirror **116***a* is configured such that radiation beam **104***h* is incident upon mirror **116***a* at an incident angle θ_5. Mirror **116***a* is configured to reflect incident radiation beam **104***h* such that radiation beam **104***i* reflected from mirror **116***a* is incident upon mirror **116***b* at an incident angle $\theta_6=2\theta_5-90°$. Mirror **116***b* is configured to reflect incident radiation beam **104***l* such that radiation beam **104***j* reflected from mirror **116***b* is incident on mirror **116***c* at the incident angle θ_5. Mirror **116***c* is configured to reflect incident radiation beam **104***j* such that radiation beam **104***k* reflected from mirror **116***c* exits compensator **116** as radiation beam **104***k* along an optical axis that aligns with the optical axis of radiation beam **104***h*. Any number of mirrors can be used in compensator **116** such that the optical axis of an incoming radiation beam and that of an outgoing radiation beam are aligned and unchanged. In an alternate embodiment of the present invention, compensator **116** includes four mirrors arranged in a manner as shown in FIG. **5**. Compensator **116** is capable of rotating at an angular velocity about an axis that aligns with the optical axes of radiation beams **104***h* and **104***k*. In some embodiments of the present invention, compensator **116** is capable of rotating in steps about an axis that aligns with the optical axes of radiation beams **104***h* and **104***k*.

[0043] Radiation beam **104***k* from compensator **116** is directed to polarizer **118** and polarizer **118** imparts diattenuation and phase retardance to radiation beam **104***k*. In one embodiment of the present invention, polarizer **118** includes mirrors **118***a*, **118***b*, and **118***c*, as shown in FIG. **4**, positioned to receive radiation beam **104***k* from compensator **116** to apply diattenuation and phase retardance. Mirrors **118***a-c* are

rigidly arranged in a housing such that the optical axis of incoming radiation beam **104***k* received by polarizer **118** aligns with the optical axis of radiation beam **104***n* exiting polarizer **118**. Mirror **118***a* is configured such that radiation beam **104***k* is incident upon mirror **118***a* at an incident angle θ_7. Mirror **118***a* is configured to reflect incident radiation beam **104***k* such that radiation beam **104***l* reflected from mirror **118***a* is incident upon mirror **118***b* at an incident angle $\theta_8=2\theta_7-90°$. Mirror **118***b* is configured to reflect incident radiation beam **104***l* such that radiation beam **104***m* reflected from mirror **118***b* is incident on mirror **118***c* at the incident angle θ_7. Mirror **118***c* is configured to reflect incident radiation beam **104***m* such that radiation beam **104***n* reflected from mirror **118***c* exits polarizer **118** as radiation beam **104***n* along an optical axis that aligns with the optical axes of radiation beams **104***h* and **104***k*. Mirrors **118***a-c* can be made from silicon, gold, platinum, and the like. Ellipsometer **100** operating at the shorter wavelengths, such as from about 10 nm to about 30 nm, may include mirrors **118***a-c* having multilayer stacks applied to optimize the reflectance and phase change.

[0044] Any number of mirrors can be used in polarizer **118** such that the optical axis of an incoming radiation beam and that of an outgoing radiation beam are aligned and unchanged. Figure illustrates an alternate polarizer **500** as used in an ellipsometer in accordance with an embodiment of the present invention. Polarizer **500** includes mirrors **500***a*, **500***b*, **500***c*, and **500***d* positioned to receive radiation beam **104***k* from compensator **116**. Mirrors **500***a-d* are rigidly arranged in a housing such that the optical axis of incoming radiation beam **104***k* received by polarizer **500** aligns with the optical axis of radiation beam **104***o* exiting polarizer **500**. Mirror **500***a* is configured such that radiation beam **104***k* is incident upon mirror **500***a*. Mirror **500***a* is configured to reflect incident radiation beam **104***k* such that radiation beam **104***l* reflected from mirror **500***a* is incident upon mirror **500***b*. Mirror **500***b* is configured to reflect incident radiation beam **104***l* such that radiation beam **104***m* reflected from mirror **500***b* is incident on mirror **500***c*. Mirror **500***c* is configured to reflect incident radiation beam **104***m* such that radiation beam **104***n* reflected from mirror **500***c* is incident on mirror **500***d*. Mirror **500***d* is configured to reflect incident radiation beam **104***n* such that radiation beam **104***o* reflected from mirror **500***c* exits polarizer **500** as radiation beam **104***o* along an optical axis that aligns with the optical axis of radiation beams **104***h* and **104***k*.

[0045] Fewer reflective elements in polarization state analyzer **108** may be used to reduce the losses incurred at each mirror reflection. In some embodiments of the present invention, polarizers **112** or **118** may be replaced with Brewster mirrors. FIG. **6** illustrates a polarization state analyzer **600** in accordance with an alternate embodiment of the present invention, which includes a compensator **602**, Brewster mirror **604**, and a detector **606**. Compensator **602** is similar to compensator **116**, as shown in FIGS. **1** and **4**, and receives radiation beam **104***h* reflected from sample artifact front surface positioned on sample holder **102**. All other disclosed embodiments of compensator **116** could also apply to compensator **602**. Compensator **602** includes mirrors **602***a*, **602***b*, and **602***c*, as shown in FIG. **6**, positioned to receive radiation beam **104***h* reflected from sample artifact **102** front surface and redirect as radiation beam **104***k* along an optical axis that aligns with the optical axis of radiation beam **104***h* after reflections from mirrors **602***a-c*,

as further shown in FIG. **6**. Compensator **602** is capable of rotating about an axis that aligns with the optical axes of radiation beams **104***h* and **104***k*. Radiation beam **104***k* from compensator **602** is transmitted to Brewster mirror **604** and Brewster mirror **604** reflects primarily s-polarized radiation beam **104***l* to detector **606**. Brewster mirror **604** can be made from silicon, gold, platinum, and the like. Ellipsometer **100** operating at the shorter wavelengths, such as from about 10 nm to about 30 nm, may include mirrors **604** having multilayer stacks applied to optimize the reflectance.

[0046] Referring back to FIGS. **1** and **4**, detector **120** is positioned along an axis that aligns with the optical axes of radiation beams **104***h*, **104***k* and **104***n*, as further shown in FIG. **1**, to detect radiation beam **104***n* exiting polarizer **118**. Detector **120** measures signals for N rotation angles of compensator **114** of polarization state generator **106** and M rotation angles of compensator **116** of polarization state analyzer **108**. Processor **110** determines a M×N matrix corresponding to N rotation angles of compensator **114** and M rotation angles of compensator **116**. Processor **110** further determines a Mueller matrix for reflection by sample artifact **102** using Equation (6) provided below. The Mueller matrix is a function of the angle of radiation beam **104***g* exiting compensator **114** and incident upon a front surface of a sample artifact positioned on sample holder **102**. For anisotropic media or periodic nanostructures, the Mueller matrix is also a function of azimuthal rotation of sample artifact about its surface normal.

[0047] Optical reflection from an isotropic medium can be described by two complex-valued, wavelength-dependent coefficients r_s and r_p that represent the ratios of the electric field amplitudes upon reflection for s and p polarized light, respectively. Here, s polarization refers to optical radiation with an electric field perpendicular to the plane of incidence, p polarization refers to optical radiation with an electric field parallel to the plane of incidence. Coefficients r_s and r_p can be determined from Fresnel's equations for any incident angle θ for materials whose complex-valued indices of refraction $\tilde{n}=n+ik$ are known, where n and k are referred to as optical constants:

$$r_s = \frac{\cos\theta - \left(\tilde{n}^2 - \sin^2\theta\right)^{1/2}}{\cos\theta + \left(\tilde{n}^2 - \sin^2\theta\right)^{1/2}} \tag{1}$$

$$r_p = \frac{\tilde{n}^2\cos\theta - \left(\tilde{n}^2 - \sin^2\theta\right)^{1/2}}{\tilde{n}^2\cos\theta + \left(\tilde{n}^2 - \sin^2\theta\right)^{1/2}} \tag{2}$$

[0048] The square of the complex-valued index of refraction is referred to as the dielectric function. Other expressions for the coefficients r_s and r_p can be used when the material has multiple interfaces, such as with thin films, or when the indices are graded.

[0049] Quantities that describe optical radiation intensity can be represented polarimetrically by a Stokes vector,

$$S = \begin{pmatrix} \langle |E_s|^2 \rangle + \langle |E_p|^2 \rangle \\ \langle |E_s|^2 \rangle - \langle |E_p|^2 \rangle \\ \langle 2\mathrm{Re}[E_s E_p^*] \rangle \\ \langle 2\mathrm{Im}[E_s E_p^*] \rangle \end{pmatrix} \tag{3}$$

[0050] where E_s and E_p represent the s and p components of the electric field, respectively. The first component represents the total intensity, the second and third components represent linear polarization, and the fourth component represents circular polarization. Reflection from a surface can be represented by a Mueller matrix, representing the linear relationship between the incoming and outgoing Stokes vectors, which for a surface having reflection coefficients r_s and r_p is

$$M = \begin{pmatrix} \langle |r_s|^2 + |r_p|^2 \rangle/2 & \langle |r_s|^2 - |r_p|^2 \rangle/2 & 0 & 0 \\ \langle |r_s|^2 - |r_p|^2 \rangle/2 & \langle |r_s|^2 + |r_p|^2 \rangle/2 & 0 & 0 \\ 0 & 0 & \langle \mathrm{Re}(r_s r_p^*) \rangle & \langle \mathrm{Im}(r_s r_p^*) \rangle \\ 0 & 0 & -\langle \mathrm{Im}(r_s r_p^*) \rangle & \langle \mathrm{Re}(r_s r_p^*) \rangle \end{pmatrix} \tag{4}$$

[0051] For anisotropic materials and for periodic structures, the Mueller matrix has fewer elements that are zero than those shown in Equation (2). For a single interface between vacuum and a material having a complex-valued index of refraction ñ, the reflection coefficients are given by Equations (1) and (2) above.

[0052] Ellipsometer **100** operates by impinging a series of Stokes vectors generated by polarization state generator **106** onto the unknown sample under test and sensing the reflected light with a series of Stokes vector sensitivities analyzed by polarization state analyzer **108**. The measurement matrix can be represented by

$$P=AMW \tag{5}$$

[0053] where W is a 4×N matrix whose rows include the N Stokes vectors applied to the sample and A is a M×4 matrix whose columns include the M Stokes vector sensitivities. P is a M×N matrix that contains the measurements for each combination of incident and sensed polarization. The unknown sample matrix M can then be determined from

$$M=A^{-1}PW^{-1} \tag{6}$$

[0054] A^{-1} and W^{-1} can be determined from A and W in Equation (5) provided A and W are well-conditioned. As used herein, the term "well-conditioned" refers to a matrix having a condition number not substantially larger than $\sqrt{3}$ and that the inverse of such matrix can be calculated with reasonable accuracy. The condition number is defined as the ratio of maximum singular value to the minimum singular value in a singular value decomposition and provides a metric for a Stokes polarimeter's behavior. A preferred polarimeter has a condition number of $\sqrt{3}$.

[0055] FIG. **7** shows an exemplary plot for calculated condition number for polarizer **112** shown in FIG. **1**, wherein each of mirrors **112***a-c* and **114***a-c* are platinum mirrors and positioned with θ_1=67.5 deg. (such that θ_2=45 deg.), θ_3=82 deg. (such that θ_4=74 deg.), and compensator **114** is rotated from 0 deg. (where the planes of incidence of all six reflections coincide) to 157.5 deg. with increments of 22.5 deg. The condition number for this configuration of platinum mirrors is less than 10 for wavelengths longer than 36 nm. Other mirror materials, or combinations of different materials for each mirror, used with varying angles θ_1 and θ_3 (and thus, θ_2 and θ_4) can yield different condition numbers and improved condition numbers or increase the throughput of polarization state generator **106**.

[0056] When unpolarized radiation beam **104a** enters polarizer **112**, the Stokes vector transmitting through polarizer **112** and compensator **114** and emerging as radiation beam **104g** when compensator **114** is rotated an angle α from polarizer **112**, is

$$R(-\alpha)M(\theta_3,\tilde{n})M(\theta_4,\tilde{n})M(\theta_3,\tilde{n})R(\alpha)M(\theta_1,\tilde{n})M(\theta_2,\tilde{n})M(\theta_1,\tilde{n})S_{unpol}$$

[0057] where M(θ, ñ) is obtained from Equation (4) using Equations (1) and (2), and R(α) is the rotation matrix

$$R(\alpha) = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos2\alpha & \sin2\alpha & 0 \\ 0 & -\sin2\alpha & \cos2\alpha & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} \qquad (7)$$

[0058] FIG. **8** shows an ellipsometer **800** in accordance with a second embodiment of the present invention. Ellipsometer for probing a sample artifact includes a sample holder **802**, a radiation source **804**, polarization state generator **806** and a polarization state analyzer **808** and a processor **810** arranged in a manner as shown in FIG. **8**. Radiation source **804** is similar to radiation source **104**, as shown in FIG. **1**, which emits radiation beam **804a** to polarization state generator **806**. Polarization state generator **806** includes a Brewster mirror **812** and a compensator **814**. Brewster mirror **812** is positioned to receive radiation beam **804a** from radiation source **804** and reflect a s-polarized radiation beam **804b** to compensator **814** while no p-polarized radiation beam enters and exits Brewster mirror **812**.

[0059] Compensator **814** is similar to compensator **116**, as shown in FIGS. **1** and **4**, and receives radiation beam **804b** reflected from Brewster mirror **812**. All other disclosed embodiments of compensator **116** could also apply to compensator **814**. Compensator **814** includes mirrors **814a**, **814b**, and **814c**, as shown in FIG. **8**, positioned to receive radiation beam **804b** reflected from Brewster mirror **812** and redirect radiation beam **804e** reflected from mirrors **814a-c** along an optical axis that aligns with the optical axis of radiation beam **804b**, as further shown in FIG. **8**. Compensator **814** is capable of rotating about an axis that aligns with the optical axes of radiation beams **804b** and **804e**.

[0060] Radiation beam **804e** exiting compensator **814** is directed to sample artifact positioned on sample holder **802**. Sample holder **802** is positioned such that radiation beam **804e** exiting compensator **814** is incident on a surface of sample artifact. Sample holder **802** can be rotated such that radiation beam **804e** is incident on sample artifact front surface at a predetermined incident angle. In one embodiment, sample holder **802** can be rotated azimuthally about its surface normal. Radiation beam **804e** incident on sample artifact front surface is reflected as radiation beam **804f** into polarization state analyzer **808**.

[0061] Polarization state analyzer **808** includes a compensator **816**, a Brewster mirror **818** and a detector **820** and rotates about an axis passing through the location where radiation beam **804e** strikes the front surface of the sample artifact positioned on sample holder **802**, as further shown in FIG. **8**. Compensator **816** is similar to compensator **116**, as shown in FIGS. **1** and **4**, and receives radiation beam **804f** reflected from sample artifact front surface. All other disclosed embodiments of compensator **116** could also apply to compensator **816**. Compensator **816** includes mirrors **816a**,

816b, and **816c**, as shown in FIG. **8**, positioned to receive radiation beam **804f** reflected from sample artifact front surface and redirect radiation beam **804i** reflected from mirrors **816a-c** along an optical axis that aligns with the optical axes of radiation beam **804f**, as further shown in FIG. **8**. Compensator **816** is capable of rotating about an axis that aligns with the optical axes of radiation beams **804f** and **804i**. Radiation beam **804i** from compensator **816** is transmitted to Brewster mirror **818** and Brewster mirror **818** reflects primarily s-polarized radiation beam **804j** to detector **820**.

[0062] Detector **820** is similar to detector **120**, and is positioned to detect s-polarized radiation beam **804j** reflected by Brewster mirror **818**, as further shown in FIG. **8**. Detector **820** measures signals for N rotation angles of compensator **814** of polarization state generator **806** and M rotation angles of compensator **816** of polarization state analyzer **808**. Processor **810** determines a M×N matrix corresponding to N rotation angles of compensator **814** and M rotation angles of compensator **816**. Processor **810** further determines a Mueller matrix for reflection by sample artifact as a function of the angle radiation beam **804f** exiting compensator **814** and incident upon sample artifact. For anisotropic media or periodic nanostructures, it is also a function of azimuthal rotation of sample artifact about its surface normal.

[0063] Ellipsometers in accordance with the present invention, as shown in FIGS. **1** and **8**, can be calibrated using an arrangement of optical elements as shown in FIG. **9** and eigenvalue calibration methods known in the art to obtain the matrices A and W, as shown in Equation (5), and data reduction matrices A^{-1} and W^{-1}, as shown in Equation (6). The arrangement of optical elements shown in FIG. **9** is similar to the arrangement of optical elements shown in FIG. **8** with sample artifact and sample holder **802** removed such that polarization state analyzer **908** is positioned to directly measure radiation beam **902h** transmitted by rotating compensator **914** of polarization state generator **904**. An additional rotating compensator **906** is positioned between the polarization state generator **904** and polarization state analyzer **908**, as shown in FIG. **9**. For each of at least two rotations of compensator **906**, detector **920** measures signals corresponding to N rotation angles of compensator **914** of polarization state generator **904** and M rotation angles of compensator **916** of polarization state analyzer **908**. Processor **910** determines a M×N matrix corresponding to N rotation angles of compensator **914** and M rotation angles of compensator **916**. The additional compensator **906** exhibits net diattenuation and retardance to yield a suitable calibration. Detector **920** further measures signals corresponding to N rotation angles of compensator **914** and M rotation angles of compensator **916** in an arrangement without including compensator **906**, and processor **910** determines an additional M×N matrix corresponding to the N rotation angles of compensator **914** and the M rotation angles of compensator **916**.

[0064] In embodiments wherein radiation beam from a radiation source is naturally polarized, a polarizer is optional in a polarization state generator for the operation of an ellipsometer in accordance with the present invention and, as shown in FIG. **10**, a polarization state generator need only include a compensator and the naturally polarized radiation beam from radiation source can be transmitted directly to the compensator. FIG. **10** shows an ellipsometer **1000** in accor-

dance with an alternate embodiment of the present invention for probing a sample artifact. Ellipsometer **1000** includes a sample holder **1002**, a radiation source **1004**, polarization state generator **1006**, a polarization state analyzer **1008** and a processor **1010** arranged in a manner as shown in FIG. **10**. Radiation source **1004** emits radiation beam **1004***a* that is naturally polarized to polarization state generator **1006**. Polarization state generator **1006** includes a compensator **1012** positioned to receive radiation beam **1004***a* from radiation source **1004** and reflect a radiation beam **1004***d* having a phase retardance to sample artifact positioned on sample holder **1002**.

[0065] Compensator **1012** is similar to compensator **116**, as shown in FIGS. **1** and **4**, and receives radiation beam **1004***a* from radiation source **1004**. All other disclosed embodiments of compensator **116** could also apply to compensator **1012**. Compensator **1012** includes mirrors **1012***a*, **1012***b*, and **1012***c*, as shown in FIG. **10**, positioned to receive radiation beam **1004***a* from radiation source **1004** and redirect radiation beam **1004***d* reflected from mirrors **1012***a-c* along an optical axis that aligns with the optical axis of radiation beam **1004***a*, as further shown in Figure Compensator **1012** is capable of rotating about an axis that aligns with the optical axes of radiation beams **1004***a* and **1004***d*.

[0066] Radiation beam **1004***d* exiting compensator **1012** is directed to sample artifact positioned on sample holder **1002**. Sample holder **1002** is positioned such that radiation beam **1004***d* exiting compensator **1012** is incident on a surface of sample artifact. Sample holder **1002** can be rotated such that radiation beam **1004***d* is incident on sample artifact front surface at a predetermined incident angle. In one embodiment, sample holder **1002** can be rotated azimuthally about its surface normal. Radiation beam **1004***d* incident on sample artifact front surface is reflected as radiation beam **1004***e* into polarization state analyzer **1008**.

[0067] Polarization state analyzer **1008** includes a compensator **1014**, a polarizer **1016** and a detector **1018**, and rotates about an axis passing through the location where radiation beam **1004***d* strikes the front surface of the sample artifact positioned on sample holder **1002**, as further shown in FIG. **10**. Compensator **1014** is similar to compensator **116**, as shown in FIGS. **1** and **4**, and receives radiation beam **1004***e* reflected from sample artifact front surface. All other disclosed embodiments of compensator **116** could also apply to compensator **1014**. Compensator **1014** includes mirrors **1014***a*, **1014***b*, and **1014***c*, as shown in FIG. **10**, positioned to receive radiation beam **1004***e* reflected from sample artifact front surface and redirect radiation beam **1004***h* reflected from mirrors **1014***a-c* along an optical axis that aligns with the optical axis of radiation beam **1004***e*, as further shown in FIG. **10**. Compensator **1014** is capable of rotating about an axis that aligns with the optical axes of radiation beams **1004***e* and **1004***h*. Radiation beam **1004***h* from compensator **1014** is transmitted to polarizer **1016**. Polarizer **1016** is similar to polarizer **118**, and is positioned to reflect primarily s-polarized radiation beam **1004***k* to detector **1018**.

[0068] Detector **1018** is similar to detector **120**, and is positioned to detect s-polarized radiation beam **1004***k* reflected by polarizer **1016**, as further shown in FIG. **10**. Detector **1018** measures signals for N rotation angles of compensator **1012** of polarization state generator **1006** and M rotation angles of compensator **1014** of polarization state analyzer **1008**. Processor **1010** determines a M×N matrix

corresponding to N rotation angles of compensator **1012** and M rotation angles of compensator **1014**. Processor **1010** further determines a Mueller matrix for reflection by sample artifact as a function of the angle radiation beam **1004***d* exiting compensator **1012** and incident upon sample artifact. For anisotropic media or periodic nanostructures, it is also a function of azimuthal rotation of sample artifact about its surface normal.

[0069] It should be understood that arrangement of optical elements in ellipsometers, as shown herein, are not exhaustive and that other optical elements can be utilized as well before, after, or between any of the illustrated optical elements.

[0070] Ellipsometers in accordance with embodiments of the present invention can operate at VUV and EUV wavelengths and enable measurements of the Mueller matrix associated with the reflection of radiation in VUV and EUV wavelengths, which can be used to determine optical constants of materials, the thickness and optical constants of thin films, and the dimensions (such as height, width, side wall angle) of periodic microstructures. Ellipsometers in accordance with embodiments of the present invention has several advantages over previous ellipsometers. Scatterometry, or the use of spectroscopic ellipsometry for the measurement of the dimensions of nanopatterned structures, is a critical process control technology used by the semiconductor industry. Ellipsometers in accordance with embodiments of the present invention provide paths toward implementing scatterometry in wavelengths shorter than about 150 nm, and in particular, in the deep ultraviolet or extreme ultraviolet spectral regions. Ellipsometers in accordance with embodiments of the present invention can be used to characterize high-quality multilayer optical systems to provide complete knowledge of the polarization properties, such as the change in phase at the interfaces of a multilayer, which is necessary for the optical imaging in EUV-lithography and currently is simulated from coating models. Mueller matrix formalism can describe reflection from disordered materials, such as patterns with roughness that cause depolarization. As industrial processes become more complex, ellipsometers in accordance with embodiments of the present invention operating at VUV or EUV wavelengths can be used to improve the characterization of nanostructured materials with roughness.

[0071] Ellipsometers in accordance with one or more embodiments of the present invention can be adapted to a variety of configurations. It is thought that ellipsometers in accordance with various embodiments of the present invention and many of its attendant advantages will be understood from the foregoing description and it will be apparent that various changes may be made without departing from the spirit and scope of the invention or sacrificing all of its material advantages, the form hereinbefore described being merely a preferred or exemplary embodiment thereof.

[0072] Those familiar with the art will understand that embodiments of the invention may be employed, for various specific purposes, without departing from the essential substance thereof. The description of any one embodiment given above is intended to illustrate an example rather than to limit the invention. This above description is not intended to indicate that any one embodiment is necessarily preferred over any other one for all purposes, or to limit the scope of the invention by describing any such embodiment, which invention scope is intended to be determined by the claims,

properly construed, including all subject matter encompassed by the doctrine of equivalents as properly applied to the claims.

What is claimed is:

1. An ellipsometer for investigating a sample, said ellipsometer comprising:

a radiation source for generating a non-polarized radiation beam;

a polarization state generator comprising:

a first polarizer comprising a first plurality of mirrors positioned to modify the non-polarized radiation beam to a first polarized radiation beam, wherein an optical axis of the first polarized radiation beam is substantially aligned with an optical axis of the non-polarized radiation beam; and

a first rotating compensator comprising a second plurality of mirrors for altering the first polarized radiation beam to a second polarized radiation beam having a first phase retardance, wherein an optical axis of the second polarized radiation beam is substantially aligned with the optical axis of the first polarized radiation beam;

a sample holder for positioning a first surface of the sample to receive the second polarized radiation beam from the first rotating compensator, wherein the first surface of the sample reflects a third polarized radiation beam;

a polarization state analyzer comprising:

a second rotating compensator comprising a third plurality of mirrors for altering the third polarized radiation beam to a fourth polarized radiation beam having a second phase retardance, wherein an optical axis of the fourth polarized radiation beam is substantially aligned with the optical axis of the third polarized radiation beam; and

a second polarizer comprising a fourth plurality of mirrors for modifying the fourth polarized radiation beam to a fifth polarized radiation beam, wherein an optical axis of the fifth polarized radiation beam is substantially aligned with an optical axis of the fourth polarized radiation beam;

a detector for measuring a plurality of first signals for a plurality of first rotation angles of the first rotating compensator and a plurality of second signals for a plurality of second rotation angles of the second rotating compensator; and

a processor for determining a Mueller matrix from the plurality of the first rotation angles of the first rotating compensator and the plurality of the second rotation angles of the second rotating compensator.

2. The ellipsometer of claim 1, wherein the non-polarized radiation beam has a wavelength in vacuum ultraviolet region of an electromagnetic spectrum.

3. The ellipsometer of claim 1, wherein the non-polarized radiation beam has a wavelength in extreme ultraviolet region of an electromagnetic spectrum.

4. The ellipsometer of claim 1, wherein at least one of the first polarizer, the second polarizer, the first compensator and the second compensator comprise three mirrors.

5. The ellipsometer of claim 1, wherein at least one of the first polarizer, the second polarizer, the first compensator and the second compensator comprise four mirrors.

6. The ellipsometer of claim 1, wherein the first plurality of mirrors comprise:

a first mirror positioned to reflect the non-polarized radiation beam incident on the first mirror as a first reflected radiation beam;

a second mirror positioned to reflect the first reflected radiation beam incident on the second mirror as a second reflected radiation beam; and

a third mirror positioned to reflect the second reflected radiation beam incident on the third mirror as the first polarized radiation beam;

wherein the second plurality of mirrors comprise:

a fourth mirror positioned to reflect the first polarized radiation beam incident on the fourth mirror as a third reflected radiation beam;

a fifth mirror positioned to reflect the third reflected radiation beam incident on the fifth mirror as a fourth reflected radiation beam; and

a sixth mirror positioned to reflect the fourth reflected radiation beam incident on the sixth mirror as the second polarized radiation beam having the first phase retardance;

wherein the third plurality of mirrors comprise:

a seventh mirror positioned to reflect the third polarized radiation beam incident on the seventh mirror as fifth reflected radiation beam;

an eighth mirror positioned to reflect the fifth reflected radiation beam incident on the eighth mirror as a sixth reflected radiation beam; and

a ninth mirror positioned to reflect the sixth reflected radiation beam incident on the ninth mirror as the fourth polarized radiation beam having the second phase retardance; and

wherein the fourth plurality of mirrors comprise:

a tenth mirror positioned to reflect the fourth polarized radiation beam incident on the tenth mirror as a seventh reflected radiation beam;

an eleventh mirror positioned to reflect the seventh reflected radiation beam incident on the eleventh mirror as an eighth reflected radiation beam; and

a twelfth mirror positioned to reflect the eighth reflected radiation beam incident on the twelfth mirror as the fourth polarized radiation beam.

7. The ellipsometer of claim 6, wherein the first plurality of mirrors further comprises a thirteenth mirror positioned to receive one of the non-polarized radiation beam, the first reflected radiation beam and the second reflected radiation beam, wherein the first, the second, the third and the thirteenth mirrors modify the non-polarized radiation beam to the first polarized radiation beam.

8. The ellipsometer of claim 6 or 7, wherein the second plurality of mirrors further comprises a fourteenth mirror positioned to receive one of the first polarized radiation beam, the third reflected radiation beam and the fourth reflected radiation beam, wherein the fourth, the fifth, the sixth and the fourteenth mirrors alter the first polarized radiation beam to the second polarized radiation beam having the first phase retardance.

9. The ellipsometer of claim 6 or 7, wherein the third plurality of mirrors further comprises a fourteenth mirror positioned to receive one of the third polarized radiation beam, the fifth reflected radiation beam and the sixth reflected radiation beam, wherein the seventh, the eighth, the ninth and the fourteenth mirrors alter the third polarized radiation beam to the fourth polarized radiation beam having the second phase retardance.

10. The ellipsometer of claim **6** or **7**, wherein the fourth plurality of mirrors further comprises a fourteenth mirror positioned to receive one of the fourth polarized radiation beam, the seventh reflected radiation beam and the eighth reflected radiation beam, wherein the tenth, the eleventh, the twelfth and the fourteenth mirrors modify the fourth polarized radiation beam to the fifth polarized radiation beam.

11. The ellipsometer of claim **1**, wherein the first rotating compensator is rotated about an axis substantially aligned with the optical axes of the first and the second polarized radiation beams, and wherein the second compensator is rotated about an axis substantially aligned with the optical axes of the third and the fourth polarized radiation beams.

12. The ellipsometer of claim **1**, wherein the polarization state analyzer is rotated about an axis passing through a location the second polarized radiation beam is received on the first surface of the sample positioned on the sample holder, wherein the sample holder rotates the sample about the axis passing through the location the second polarized radiation beam is received on the first surface of the sample positioned on the sample holder, wherein the rotation of the sample is about one-half of the rotation of the polarization state analyzer, and wherein the rotating the polarization state analyzer adjusts an angle of incidence of the second polarized radiation beam on the first surface of the sample positioned on the sample holder and an angle of reflection of the third polarized radiation beam.

13. The ellipsometer of claim **1**, wherein the sample holder rotates the sample in an azimuthal direction about an axis normal to the first surface of the sample.

14. An ellipsometer for investigating a sample, said ellipsometer comprising:

a radiation source for generating a non-polarized radiation beam having a wavelength from about 10 nm to about 240 nm;

a first polarizer for modifying the non-polarized radiation beam to a first polarized radiation beam, wherein an optical axis of the first polarized radiation beam is substantially aligned with an optical axis of the non-polarized radiation beam, wherein the first polarizer comprises:

a first mirror positioned to reflect the non-polarized radiation beam incident on the first mirror as a first reflected radiation beam;

a second mirror positioned to reflect the first reflected radiation beam incident on the second mirror as a second reflected radiation beam; and

a third mirror positioned to reflect the second reflected radiation beam incident on the third mirror as the first polarized radiation beam;

a first rotating compensator for altering the first polarized radiation beam to a second polarized radiation beam having a first phase retardance, wherein an optical axis of the second polarized radiation beam is substantially aligned with the optical axis of the first polarized radiation beam, wherein the first compensator is rotated about an axis substantially aligned with the optical axes of the first and the second polarized radiation beams, wherein the first rotating compensator comprises:

a fourth mirror positioned to reflect the first polarized radiation beam incident on the fourth mirror as a third reflected radiation beam, wherein the third reflected radiation beam comprises a second phase retardance;

a fifth mirror positioned to reflect the third reflected radiation beam incident on the fifth mirror as a fourth reflected radiation beam, wherein the fourth reflected radiation beam comprises a third phase retardance; and

a sixth mirror positioned to reflect the fourth reflected radiation beam incident on the sixth mirror as the second polarized radiation beam having the first phase retardance;

a sample holder for positioning a first surface of the sample to receive the second polarized radiation beam from the first rotating compensator, wherein the first surface of the sample reflects a third polarized radiation beam;

a second rotating compensator for altering the third polarized radiation beam to a fourth polarized radiation beam having a fourth phase retardance, wherein an optical axis of the fourth polarized radiation beam is substantially aligned with the optical axis of the third polarized radiation beam, wherein the second compensator is rotated about an axis substantially aligned with the optical axes of the third and the fourth polarized radiation beams, wherein the second compensator comprises:

a seventh mirror positioned to reflect the third polarized radiation beam incident on the seventh mirror as a fifth reflected radiation beam, wherein the fifth reflected radiation beam comprises a fifth phase retardance;

an eighth mirror positioned to reflect the fifth reflected radiation beam incident on the eighth mirror as a sixth reflected radiation beam, wherein the sixth reflected beam comprises a sixth phase retardance; and

a ninth mirror positioned to reflect the sixth reflected radiation beam incident on the ninth mirror as the fourth polarized radiation beam having the fourth phase retardance;

a second polarizer for modifying the fourth polarized radiation beam to a fifth polarized radiation beam, wherein an optical axis of the fifth polarized radiation beam is substantially aligned with an optical axis of the fourth polarized radiation beam, wherein the second polarizer comprises:

a tenth mirror positioned to reflect the fourth polarized radiation beam incident on the tenth mirror as a seventh reflected radiation beam;

an eleventh mirror positioned to reflect the seventh reflected radiation beam incident on the eleventh mirror as an eighth reflected radiation beam; and

a twelfth mirror positioned to reflect the eighth reflected radiation beam incident on the twelfth mirror as the fifth polarized radiation beam;

a detector for measuring a plurality of first signals for a plurality of first rotation angles of the first rotating compensator and a plurality of second signals for a plurality of second rotation angles of the second rotating compensator; and

a processor for determining a Mueller matrix from the plurality of the first rotation angles of the first rotating compensator and the plurality of the second rotation angles of the second rotating compensator.

15. The ellipsometer of claim **14**, wherein the wavelength of the non-polarized radiation beam is from about 10 nm to about 30 nm.

16. The ellipsometer of claim **14**, wherein the wavelength of the non-polarized radiation beam is from about 30 nm to about 240 nm.

17. The ellipsometer of claim **14**, wherein the second compensator and the second polarizer are rotated about an axis passing through a location the second polarized radiation beam is received on the first surface of the sample positioned on the sample holder, wherein the sample holder rotates the sample about the axis passing through the location the second polarized radiation beam is received on the first surface of the sample positioned on the sample holder, wherein the rotation of the sample is about one-half of the rotation of the polarization state analyzer, and wherein the rotating the polarization state analyzer adjusts an angle of incidence of the second polarized radiation beam on the first surface of the sample positioned on the sample holder and an angle of reflection of the third polarized radiation beam.

18. The ellipsometer of claim **14**, wherein the sample holder rotates the sample in an azimuthal direction about an axis normal to the first surface of the sample.

19. The ellipsometer of claim **14**, wherein the first polarizer further comprises a thirteenth mirror positioned to receive one of the non-polarized radiation beam, the first reflected radiation beam and the second reflected radiation beam, and wherein the first, the second, the third and the thirteenth mirrors are positioned to modify the non-polarized radiation beam to the first polarized radiation beam.

20. The ellipsometer of claim **14**, wherein the second polarizer further comprises a thirteenth mirror positioned to receive one of the fourth polarized radiation beam, the seventh reflected radiation beam and the eighth reflected radiation beam, and wherein the tenth, the eleventh, the twelfth and the thirteenth mirrors are positioned to modify the fourth polarized radiation beam to the fifth polarized radiation beam.

21. The ellipsometer of claim **14**, wherein the first polarizer further comprises a thirteenth mirror positioned to receive a ninth reflected radiation beam from the third mirror, and wherein the thirteenth mirror is positioned to reflect the ninth reflected radiation beam incident on the thirteenth mirror as the first polarized radiation beam, and wherein the second polarizer further comprises a fourteenth mirror positioned to receive a tenth reflected radiation beam from the twelfth mirror, and wherein the fourteenth mirror is positioned to reflect the tenth reflected radiation beam incident on the fourteenth mirror as the fifth polarized radiation beam.

22. An ellipsometer for investigating a sample, said ellipsometer comprising:

a radiation source for generating a non-polarized radiation beam;

a polarization state generator for modifying the non-polarized radiation beam to a first polarized radiation beam having a first phase retardance, wherein the polarization state generator comprises:

a first mirror positioned to reflect the non-polarized radiation beam incident on the first mirror as a first reflected radiation beam;

a second mirror positioned to reflect the first reflected radiation beam incident on the second mirror as a second reflected radiation beam;

a third mirror positioned to reflect the second reflected radiation beam incident on the second mirror as a third reflected radiation beam;

a fourth mirror positioned to reflect the third reflected radiation beam incident on the third mirror as a fourth reflected radiation beam; and

a first rotating compensator for altering the fourth reflected radiation beam to the first polarized radiation beam having the first phase retardance, wherein an optical axis of the first polarized radiation beam is substantially aligned with the optical axis of the non-polarized radiation beam, wherein the first compensator is rotated about an axis substantially aligned with the optical axis of the first polarized radiation beam;

a sample holder for positioning a first surface of the sample to receive the first polarized radiation beam from the polarization state generator, wherein the first surface of the sample reflects a second polarized radiation;

a polarization analyzer comprising:

a second rotating compensator for altering the second polarized radiation beam to a third polarized radiation beam having a second phase retardance, wherein an optical axis of the third polarized radiation beam is substantially aligned with the optical axis of the second polarized radiation beam, wherein the compensator is rotated about an axis substantially aligned with the optical axes of the second and the third polarized radiation beams; and

a polarizer for modifying the third polarized radiation beam to a fourth polarized radiation beam, wherein an optical axis of the fourth polarized radiation beam is substantially aligned with an optical axis of the third polarized radiation beam;

a detector for measuring a plurality of first signals for a plurality of first rotation angles of the polarization state generator and a plurality of second signals for a plurality of second rotation angles of the rotating compensator; and

a processor for determining a Mueller matrix from the plurality of the first rotation angles of the polarization state generator and the plurality of the second rotation angles of the rotating compensator.

23. The ellipsometer of claim **22**, wherein the non-polarized radiation beam has a wavelength in vacuum ultraviolet region of an electromagnetic spectrum.

24. The ellipsometer of claim **22**, wherein the non-polarized radiation beam has a wavelength in extreme ultraviolet region of an electromagnetic spectrum.

25. The ellipsometer of claim **22**, wherein the first rotating compensator comprises:

a fifth mirror positioned to reflect the fourth reflected radiation beam incident on the fifth mirror as a fifth reflected radiation beam, wherein the fifth reflected radiation beam comprises a third phase retardance;

a sixth mirror positioned to reflect the fifth reflected radiation beam incident on the sixth mirror as a sixth reflected radiation beam, wherein the fifth reflected beam comprises a fourth phase retardance; and

a seventh mirror positioned to reflect the sixth reflected radiation beam incident on the seventh mirror as the first polarized radiation beam having the first phase retardance.

26. The ellipsometer of claim **22**, wherein the second rotating compensator comprises:

a fifth mirror positioned to reflect the second polarized radiation beam incident on the fifth mirror as a fifth reflected radiation beam, wherein the fifth reflected radiation beam comprises a third phase retardance;

a sixth mirror positioned to reflect the fifth reflected radiation beam incident on the sixth mirror as a sixth reflected radiation beam, wherein the sixth reflected beam comprises a fourth phase retardance; and

a seventh mirror positioned to reflect the sixth reflected radiation beam incident on the seventh mirror as the third polarized radiation beam having the second phase retardance.

27. The ellipsometer of claim **22**, wherein the polarizer comprises:

a fifth mirror positioned to reflect the third polarized radiation beam incident on the fifth mirror as a fifth reflected radiation beam;

a sixth mirror positioned to reflect the fifth reflected radiation beam incident on the sixth mirror as a sixth reflected radiation beam; and

a seventh mirror positioned to reflect the sixth reflected radiation beam incident on the seventh mirror as the fourth polarized radiation beam.

28. The ellipsometer of claim **22**, wherein the polarizer comprises:

a fifth mirror positioned to reflect the third polarized radiation beam incident on the fifth mirror as a fifth reflected radiation beam;

a sixth mirror positioned to reflect the fifth reflected radiation beam incident on the sixth mirror as a sixth reflected radiation beam; and

a seventh mirror positioned to reflect the sixth reflected radiation beam incident on the seventh mirror as a seventh reflected radiation beam; and

an eighth mirror positioned to receive the seventh reflected radiation beam incident on the eighth mirror as the fourth polarized radiation beam.

29. The ellipsometer of claim **22**, wherein the polarization state analyzer is rotated about an axis passing through a location the second polarized radiation beam is received on the first surface of the sample positioned on the sample holder, wherein the sample holder rotates the sample about the axis passing through the location the second polarized radiation beam is received on the first surface of the sample positioned on the sample holder, wherein the rotation of the sample is about one-half of the rotation of the polarization state analyzer, and wherein the rotating the polarization state analyzer adjusts an angle of incidence of the second polarized radiation beam on the first surface of the sample positioned on the sample holder and an angle of reflection of the third polarized radiation beam.

30. The ellipsometer of claim **22**, wherein the sample holder rotates the sample in an azimuthal direction about an axis normal to the first surface of the sample.

31. An ellipsometer for investigating a sample, said ellipsometer comprising:

a radiation source for generating a non-polarized radiation beam;

a polarization state generator comprising:

a first Brewster mirror for modifying the non-polarized radiation beam to a first polarized radiation beam,

wherein the first polarized radiation beam comprises a first parallel optical component and a first orthogonal optical component;

a first rotating compensator comprising a first plurality of mirrors for altering the first polarized radiation beam to a second polarized radiation beam having a first phase retardance, wherein an optical axis of the second polarized radiation beam is substantially aligned with an optical axis of the first polarized radiation beam, wherein the first rotating compensator is rotated about an axis substantially aligned with the optical axes of the first and the second polarized radiation beams;

a sample holder for positioning a first surface of the sample to receive the second polarized radiation beam from the first rotating compensator, wherein the first surface of the sample reflects a third polarized radiation beam;

a polarization analyzer comprising:

a second rotating compensator comprising a second plurality of mirrors for altering the third polarized radiation beam to a fourth polarized radiation beam having a second phase retardance, wherein an optical axis of the fourth polarized radiation beam is substantially aligned with an optical axis of the third polarized radiation beam, wherein the second compensator is rotated about an axis substantially aligned with the optical axes of the third and the fourth polarized radiation beams; and

a second Brewster mirror for modifying the fourth polarized radiation beam to a fifth polarized radiation beam, wherein the fifth polarized radiation beam comprises a second parallel optical component and a second orthogonal optical component, wherein an optical axis of the fifth polarized radiation beam is substantially aligned with the optical axis of the fourth polarized radiation beam,

wherein the polarization state analyzer is rotated about an axis passing through a location the second polarized radiation beam is received on the first surface of the sample positioned on the sample holder, wherein the sample holder rotates the sample about the axis passing through the location the second polarized radiation beam is received on the first surface of the sample positioned on the sample holder, wherein the rotation of the sample is about one-half of the rotation of the polarization state analyzer, and wherein the rotating the polarization state analyzer adjusts an angle of incidence of the second polarized radiation beam on the first surface of the sample positioned on the sample holder and an angle of reflection of the third polarized radiation beam;

a detector for measuring a plurality of first signals for a plurality of first rotation angles of the first rotating compensator and a plurality of second signals for a plurality of second rotation angles of the second rotating compensator; and

a processor for determining a Mueller matrix from the plurality of the first rotation angles of the first rotating compensator and the plurality of the second rotation angles of the second rotating compensator.

32. The ellipsometer of claim **31**, wherein the non-polarized radiation beam has a wavelength in vacuum ultraviolet region of an electromagnetic spectrum.

33. The ellipsometer of claim **31**, wherein the non-polarized radiation beam has a wavelength in extreme ultraviolet region of an electromagnetic spectrum.

34. The ellipsometer of claim **31**, wherein the first plurality of mirrors comprises:
    a first mirror positioned to reflect the non-polarized radiation beam incident on the first mirror as a first reflected radiation beam;
    a second mirror positioned to reflect the first reflected radiation beam incident on the second mirror as a second reflected radiation beam; and
    a third mirror positioned to reflect the second reflected radiation beam incident on the third mirror as the first polarized radiation beam having the first phase retardance.

35. The ellipsometer of claim **34**, wherein the second plurality of mirrors comprises:
    a fourth mirror positioned to reflect the first polarized radiation beam incident on the fourth mirror as a third reflected radiation beam;
    a fifth mirror positioned to reflect the third reflected radiation beam incident on the fifth mirror as a fourth reflected radiation beam; and
    a sixth mirror positioned to reflect the fourth reflected radiation beam incident on the sixth mirror as the second polarized radiation beam having the second phase retardance.

36. An ellipsometer for investigating a sample, said ellipsometer comprising:
    a radiation source for generating a first polarized radiation beam having a wavelength from about 10 nm to about 240 nm in an electromagnetic spectrum;
    a first rotating compensator for altering the first polarized radiation beam to a second polarized radiation beam, wherein an optical axis of the second polarized radiation beam is substantially aligned with the optical axis of the first polarized radiation beam, wherein the first compensator is rotated about an axis substantially aligned with the optical axes of the first and the second polarized radiation beams, wherein the first rotating compensator comprises:
        a first mirror positioned to reflect the first polarized radiation beam incident on the first mirror as a first reflected radiation beam, wherein the first reflected radiation beam comprises a first phase retardance;
        a second mirror positioned to reflect the first reflected radiation beam incident on the second mirror as a second reflected radiation beam, wherein the second reflected radiation beam comprises a second phase retardance; and
        a third mirror positioned to reflect the second reflected radiation beam incident on the sixth mirror as the second polarized radiation beam having a third phase retardance;
    a sample holder for positioning a first surface of the sample to receive the second polarized radiation beam from the first rotating compensator, wherein the first surface of the sample reflects a third polarized radiation beam;
    a second rotating compensator for altering the third polarized radiation beam to a fourth polarized radiation beam, wherein an optical axis of the fourth polarized radiation beam is substantially aligned with the optical axis of the third polarized radiation beam, wherein the

second compensator is rotated about an axis substantially aligned with the optical axes of the third and the fourth polarized radiation beams, wherein the second compensator comprises:
        a fourth mirror positioned to reflect the third polarized radiation beam incident on the fourth mirror as a third reflected radiation beam, wherein the third reflected radiation beam comprises a fourth phase retardance;
        a fifth mirror positioned to reflect the third reflected radiation beam incident on the fifth mirror as a fourth reflected radiation beam, wherein the fourth reflected beam comprises a fifth phase retardance; and
        a sixth mirror positioned to reflect the fourth reflected radiation beam incident on the sixth mirror as the fourth polarized radiation beam having a sixth phase retardance;
    a polarizer for modifying the fourth polarized radiation beam to a fifth polarized radiation beam, wherein an optical axis of the fifth polarized radiation beam is substantially aligned with an optical axis of the fourth polarized radiation beam, wherein the second polarizer comprises:
        a seventh mirror positioned to reflect the fourth polarized radiation beam incident on the seventh mirror as a fifth reflected radiation beam;
        an eighth mirror positioned to reflect the fifth reflected radiation beam incident on the eighth mirror as a sixth reflected radiation beam; and
        a ninth mirror positioned to reflect the sixth reflected radiation beam incident on the ninth mirror as the fifth polarized radiation beam;
    a detector for measuring a plurality of first signals for a plurality of first rotation angles of the first rotating compensator and a plurality of second signals for a plurality of second rotation angles of the second rotating compensator; and
    a processor for determining a Mueller matrix from the plurality of the first rotation angles of the first rotating compensator and the plurality of the second rotation angles of the second rotating compensator.

37. The ellipsometer of claim **36**, wherein the wavelength of the non-polarized radiation beam is from about 10 nm to about 30 nm.

38. The ellipsometer of claim **36**, wherein the wavelength of the non-polarized radiation beam is from about 30 nm to about 240 nm.

39. The ellipsometer of claim **36**, wherein the second compensator and the polarizer are rotated about an axis passing through a location the second polarized radiation beam is received on the first surface of the sample positioned on the sample holder, wherein the sample holder rotates the sample about the axis passing through the location the second polarized radiation beam is received on the first surface of the sample positioned on the sample holder, wherein the rotation of the sample is about one-half of the rotation of the polarization state analyzer, and wherein the rotating the polarization state analyzer adjusts an angle of incidence of the second polarized radiation beam on the first surface of the sample positioned on the sample holder and an angle of reflection of the third polarized radiation beam.

40. The ellipsometer of claim **36**, wherein the sample holder rotates the sample in an azimuthal direction about an axis normal to the first surface of the sample.

41. The ellipsometer of claim **36**, wherein the polarizer further comprises a tenth mirror positioned to receive a seventh reflected radiation beam from the ninth mirror, and wherein the tenth mirror is positioned to reflect the seventh reflected radiation beam incident on the tenth mirror as the fifth polarized radiation beam.

*   *   *   *   *