

SURFACE PROFILE MEASUREMENTS OF HIGHLY WARPED SAMPLES

TECHNICAL FIELD

[0001] The present disclosure relates generally to surface profile measurements and, more particularly, to surface profile measurements of highly warped samples.

BACKGROUND

[0002] Optical interferometry is a flexible and sensitive tool for measuring the surface profile of a sample. In some applications in which light transparent to the sample of interest is used, optical interferometry may further provide surface profiles of multiple surfaces in the sample and/or a measurement of sample thickness. However, the measurement range of typical metrology tools based on optical interferometry may be insufficient to measure the surface profile of highly warped samples. Therefore, it may be desirable to provide systems and methods to cure the deficiencies of typical surface profiling techniques.

SUMMARY

[0003] A metrology tool is disclosed in accordance with one or more illustrative embodiments of the present disclosure. In one illustrative embodiment, the metrology tool includes an illumination source to generate an illumination beam. In another illustrative embodiment, the metrology tool includes a beam shaper including one or more adjustable optical elements to direct the illumination beam to a sample. In another illustrative embodiment, the metrology tool includes one or more measurement channels to receive reflected light from the sample through the beam shaper and generate one or more shearing interferograms on one or more detectors based on the reflected light, where the reflected light is in a collimated state when the one or more adjustable optical elements are in a default configuration and a top surface of the sample is orthogonal to an optical axis of the beam shaper. In another illustrative embodiment, the metrology tool includes a controller communicatively coupled to the beam shaper and the one or more

measurement channels. In another illustrative embodiment, the controller adjusts the configuration of the one or more adjustable optical elements of the beam shaper to provide a selected angular profile of the illumination beam on the sample to at least partially compensate for deviations of the reflected light from the collimated state. In another illustrative embodiment, the controller generates an output surface profile measurement of the top surface of the sample based on the one or more shearing interferograms.

[0004] A metrology tool is disclosed in accordance with one or more illustrative embodiments of the present disclosure. In one illustrative embodiment, the metrology tool includes a shearing interferometer. In another illustrative embodiment, the shearing interferometer includes an illumination source to generate an illumination beam. In another illustrative embodiment, the shearing interferometer includes a beam shaper including one or more adjustable optical elements to direct the illumination beam to a sample. In another illustrative embodiment, the shearing interferometer includes one or more measurement channels to receive reflected light from the sample through the beam shaper and generate one or more shearing interferograms on one or more detectors based on the reflected light, where the reflected light is in a collimated state when the one or more adjustable optical elements are in a default configuration and a top surface of the sample is orthogonal to an optical axis of the beam shaper. In another illustrative embodiment, the metrology tool includes a coarse surface profiler including one or more profiling sensors configured to generate a coarse surface profile measurement of the top surface of the sample, where the coarse surface profile measurement has a larger measurement range than the one or more measurement channels. In another illustrative embodiment, the metrology tool includes a controller communicatively coupled to the beam shaper and the one or more measurement channels. In another illustrative embodiment, the controller adjusts the configuration of the one or more adjustable optical elements of the beam shaper to provide a selected angular profile of the illumination beam on the sample to at least partially compensate for deviations of the reflected light from the collimated state based on the coarse surface profile measurement. In another illustrative embodiment, the controller generates an output surface profile measurement of the top surface of the sample based on the one or more shearing interferograms.

[0005] A metrology method is disclosed in accordance with one or more illustrative embodiments of the present disclosure. In one illustrative embodiment, the metrology method includes measuring a coarse surface profile measurement of a top surface of a sample with a coarse surface profiler. In another illustrative embodiment, the metrology method includes placing the sample in a shearing interferometer. In another illustrative embodiment, the shearing interferometer includes an illumination source to generate an illumination beam. In another illustrative embodiment, the shearing interferometer includes a beam shaper including one or more adjustable optical elements to direct the illumination beam to a sample. In another illustrative embodiment, the shearing interferometer includes one or more measurement channels to receive reflected light from the sample through the beam shaper and generate one or more shearing interferograms on one or more detectors based on the reflected light, where the reflected light is in a collimated state when the one or more adjustable optical elements are in a default configuration and a top surface of the sample is orthogonal to an optical axis of the beam shaper. In another illustrative embodiment, the metrology method includes adjusting the configuration of the one or more adjustable optical elements of the beam shaper to provide a selected angular profile of the illumination beam on the sample to at least partially compensate for deviations of the reflected light from the collimated state based on the coarse surface profile measurement. In another illustrative embodiment, the metrology method includes generating an output surface profile measurement of the top surface of the sample based on the one or more shearing interferograms.

[0006] It is to be understood that both the foregoing general description and the following detailed description are exemplary and explanatory only and are not necessarily restrictive of the invention as claimed. The accompanying drawings, which are incorporated in and constitute a part of the specification, illustrate embodiments of the invention and together with the general description, serve to explain the principles of the invention.

BRIEF DESCRIPTION OF DRAWINGS

[0007] The numerous advantages of the disclosure may be better understood by those skilled in the art by reference to the accompanying figures in which:

FIG. 1A is a block diagram of a metrology system in accordance with one or more embodiments of the present disclosure.

FIG. 1B is a schematic view of the metrology system in accordance with one or more embodiments of the present disclosure.

FIG. 2A is a schematic view of the metrology system including a ray diagram of light through the metrology system when configured in a nominal position with a warped sample, in accordance with one or more embodiments of the present disclosure.

FIG. 2B is a schematic view of the metrology system including a ray diagram of light through the metrology system when configured in a modified position with the warped sample of FIG. 2B, in accordance with one or more embodiments of the present disclosure.

FIG. 3 is a schematic view of a coarse surface profiler in accordance with one or more embodiments of the present disclosure.

FIG. 4 is a flow diagram illustrating steps performed in a metrology method in accordance with one or more embodiments of the present disclosure.

FIG. 5 is a flow diagram illustrating sub-steps associated with adjusting an angular profile of the illumination beam on the sample in accordance with one or more embodiments of the present disclosure.

FIG. 6A is a phase map along the X direction and a phase map along the Y direction from two measurement channels of a shearing interferometer in accordance with one or more embodiments of the present disclosure.

FIG. 6B is a predicted phase map along the X direction and a predicted phase map along the Y direction associated with the contributions of an offset distribution and a mount-induced distortion, in accordance with one or more embodiments of the present disclosure.

FIG. 6C is a compensated phase map along the X direction and a compensated phase map along the Y direction associated with generated by compensating the

measured phase maps in FIG. 6A with the predicted maps in FIG. 6B, in accordance with one or more embodiments of the present disclosure.

FIG. 6D is an unwrapped phase map along the X direction and an unwrapped phase map along the Y direction, in accordance with one or more embodiments of the present disclosure.

FIG. 7 is a flow diagram illustrating sub-steps associated with adjusting an angular profile of the illumination beam on the sample in accordance with one or more embodiments of the present disclosure.

DETAILED DESCRIPTION

[0008] Reference will now be made in detail to the subject matter disclosed, which is illustrated in the accompanying drawings. The present disclosure has been particularly shown and described with respect to certain embodiments and specific features thereof. The embodiments set forth herein are taken to be illustrative rather than limiting. It should be readily apparent to those of ordinary skill in the art that various changes and modifications in form and detail may be made without departing from the spirit and scope of the disclosure.

[0009] Embodiments of the present disclosure are directed to systems and methods for measuring surface profiles of surfaces having warped surfaces. Put another way, embodiments of the present disclosure are directed to systems and methods for measuring surface profiles of surfaces having profile variations that may be near or larger than a measurement range of a standard interferometry tool, but are associated with relatively low spatial frequencies.

[0010] For example, the surface profiles of semiconductor wafers are routinely inspected at various stages of the fabrication of semiconductor devices. Such semiconductor wafers may have diameters up to 300 mm and higher with thicknesses typically below 1 mm. Further, such wafers are typically not supported on flat surfaces, but rather on sample holders having several (e.g., three) contact points with the wafer. Thus, these wafers may exhibit warping, bowing, flexing, or other shape deviations when supported

on such a sample mount that may not be indicative of the wafer shape in a fully supported state. Such shape deviations, hereinafter referred to generally as warping, may further lead to challenges when making surface profile measurements. For example, the warping may result in surface profile (e.g., surface height) deviations across the wafer that are larger than a measurement range of a typical surface profiler. This may render particular portions of the measurement invalid or may require the stitching of multiple measurements at different heights to capture a complete sample surface.

[0011] For the purposes of the present disclosure, profile deviations with low spatial frequencies relative to a lateral field of view are referred to generally as warping. It is to be understood that this terminology is used solely for illustrative purposes and should not be interpreted as limiting. For example, it is contemplated herein that profile deviations having low spatial frequencies may be intentional or otherwise present on a sample surface for reasons other than mechanical stresses. It is further to be understood that although many of the examples and descriptions in the present disclosure relate to semiconductor samples, the examples and descriptions herein related to semiconductor samples are provided solely for illustrative purposes and should not be interpreted as limiting. Rather, the systems and methods disclosed herein may be suitable for any type of material having any form factor.

[0012] Embodiments of the present disclosure are directed to a metrology tool for surface profile measurements based on shearing interferometry, where the angular profile of light incident on a sample under test is adjustable to compensate for low spatial-frequency profile deviations such as, but not limited to, deviations caused by warping of the sample. For example, a shearing interferometer may generate a surface profile of a surface by directing light (e.g., illumination or an illumination beam) to the surface, capturing light reflected by the surface, shearing the reflected light into two sheared beams, and interfering the sheared beams on a detector to generate an interferogram. In this configuration, variations in the fringes of the interferogram correlate to variations in the sample slope along a direction of shear. Further, a surface profile measurement may be generated by integrating the measured sample slope profile.

[0013] A shearing interferometer may generally include one or more optical elements to direct light to a sample, collect reflected light from the sample (e.g., retroreflected light), and direct the reflected light to or more measurement channels. In this regard, the phase distribution of the reflected light across the sample may include information associated with the topography of the sample. Further, this reflected light from the sample is directed to one or more measurement channels that include shearing optics to shear the reflected light from the sample and generate shearing interferograms along one or more measurement directions with the sheared light. A shearing interferometer for surface profilometry is generally described in U.S. Patent No. 9,784,570 issued on October 10, 2017, which is incorporated herein by reference in its entirety.

[0014] In some embodiments, a shearing interferometer includes a beam shaper and one or more measurement channels, where the beam shaper includes one or more optical elements to shape the spatial and angular profiles of illumination from an illumination source directed to the sample. For example, the beam shaper may operate as a beam expander and expand a diameter of the illumination beam to match the size of the sample. Further, the beam shaper may collect the reflected light from the sample and direct this reflected light to the one or more measurement channels. The beam shaper and the one or more measurement channels may be, but are not required to be, generally configured as described in U.S. Patent No. 9,784,570, but may include variations and additional features as disclosed herein.

[0015] It is contemplated herein that a shearing interferometer may be adjusted to compensate for warping of the sample by modifying an angular profile of the illumination directed to a sample to at least partially compensate for the warping. In some embodiments, a shearing interferometer includes one or more adjustable optical elements, where adjusting the adjustable optical elements has the effect of modifying the angular profile of the illumination directed to the sample. For example, the one or more adjustable optical elements may be, but are not required to be, integrated into the beam shaper.

[0016] In some embodiments, the adjustable optical components may be configured to provide collimated light to a sample in a default or nominal configuration. For example, light from a sample surface oriented normal to an optical axis of the beam shaper may be retroreflected back to the beam shaper as collimated light in the default configuration. In turn, the one or more measurement channels may receive collimated light from the beam shaper. However, it is contemplated herein that a warped sample surface (e.g., a surface with low spatial-frequency profile deviations) may induce deviations of the retroreflected light from the collimated state. For example, bowing of the surface may cause the retroreflected light to converge or diverge depending on the direction of the bow. More complex distortions may generate similarly more complex deviations of the angular profile of the reflected beam from the sample. These deviations will then manifest as variations in shearing interferograms in the one or more measurement channels. Depending on the extent of the warping, the deviations of the angular profile of the reflected beam from the collimated state may be sufficiently severe as to preclude (or at least negatively impact) the measurement of the surface profile of the sample across the entire field of view.

[0017] In some embodiments, one or more optical elements of the beam shaper are adjustable to provide for modification of the angular profile of the illumination directed to the sample. Further, in some embodiments, positions of at least one adjustable optical element in the beam shaper are adjusted to modify the angular profile of illumination directed to the sample to at least partially compensate for deviations of the reflected light from the collimated state. For example, the positions of at least one optical element in the beam shaper may be adjusted to collimate (or at least partially improve the collimation of) the reflected light from the sample. In this regard, the measurement channels may receive collimated light from the beam shaper (or at least light that is more collimated than would be without adjustment of the beam shaper).

[0018] In a general sense, a default or nominal configuration against which adjustments of the one or more adjustable optical elements are defined may include any selected configuration. For instance, as described above, the default configuration may correspond to a configuration providing collimated illumination to the sample. However, in another instance, the default configuration may correspond to a configuration providing

a non-collimated angular profile of illumination on the sample. In some cases, this default configuration may be based on a known or estimated warping of the sample. Further, such a configuration may be, but is not required to be, described as an optimized configuration for a particular sample or application.

[0019] It is contemplated herein that modifying the angular profile of the illumination directed to the sample may have the effect of introducing an induced offset distribution into a measured surface profile. For example, in the case that the angular profile of the illumination beam is perfectly matched to counteract warping in the sample and to provide collimated reflected light, the measurement channels would provide a surface profile measurement indicating that the sample is free of the warp. Accordingly, the surface profile provided by the measurement channels may be considered a biased measurement profile that is biased with an induced offset distribution representative of the modified angular distribution of illumination directed to the sample.

[0020] In some embodiments, a shearing interferometer may provide the biased surface profile measurement. For example, it may be useful in some applications to provide a surface profile of the sample free of the warp. In this case, the surface profile may reflect variations other than the warp such as, but not limited to, defects, surface irregularities, or fabricated features on the sample.

[0021] In some embodiments, a shearing interferometer may provide an unbiased surface profile measurement in which the induced offset distribution is removed from the biased surface profile. In this regard, the unbiased surface profile measurement may reflect the actual layout of the sample including the warp. Notably, however, the systems and methods disclosed herein may provide that that unbiased surface profile measurement may accurately capture the full layout of the sample in situations where a typical shearing interferometer would not.

[0022] In some embodiments, a shearing interferometer may provide an adjusted surface profile in which surface profile deformations due to a sample mount (e.g., a 3-pin sample mount with three contact points) or other support mechanism are removed. For example, a sample in a horizontal position supported by a 3-pin sample mount supporting

with three contact points may exhibit sag due to gravity. By way of another example, a sample mounted a vertical position with one or more edge grippers may exhibit stresses induced by the edge grippers. By way of a further example, supporting a sample on a flat surface may result in a flattening of otherwise present deformations in the sample. In a general sense, it is contemplated herein that mounting a sample using any sample mount in any configuration may introduce some deformation of the sample based on parameters such as but not limited to, the size of the sample, the composition of the sample, and the layout of the contact points on the sample holder. Further, the shape deformations associated with the sample mount may be modeled based on these parameters such that the contribution of this mount-induced deformation may optionally be removed from an output surface profile to more accurately reflect a natural shape of the sample. Further, this mount-induced distortion may contribute to, but does not necessarily contribute to, warping of the sample that may be at least partially compensated by the modification of the angular profile of illumination directed to the sample.

[0023] It is further contemplated herein that the angular profile of the illumination beam directed to the sample required to at least partially compensate for the warp (e.g., at least partially compensate from a deviation of reflected light from a collimated state) may be determined using a variety of techniques.

[0024] In some embodiments, the angular profile of the illumination beam directed to the sample is modified based on a coarse surface profile of the sample generated using a coarse surface profile metrology tool (e.g., a coarse surface profiler). For example, a coarse surface profiler may provide a surface profile measurement having a lower resolution (e.g., along the lateral or height dimensions) than the shearing interferometer, but may provide a larger measurement range. In some cases, the coarse surface profiler may have a measurement range sufficiently large to measure the full profile variations of the sample including the warp. In this regard, the measurement of the warp may be used to determine a configuration of the beam shaper suitable providing an angular profile that at least partially compensates for the warp. Additional embodiments of the present disclosure are directed to a coarse surface profiler. In some embodiments, the coarse surface profiler includes one or more sensors having a field of view smaller than the

sample. In this regard, a coarse surface profile may be generated by scanning the sample, or a portion thereof, with the sensors. In some embodiments, the coarse surface profiler is integrated into a pre-processing tool such as, but not limited to, an alignment tool or a buffer. In this regard, the coarse surface profile may be generated prior to placing the sample in the shearing interferometer for efficient processing of multiple samples.

[0025] In some embodiments, the angular profile of the illumination beam directed to the sample is modified based on one or more surface profile measurements generated by the shearing interferometer. For example, the surface profile (or one or more shearing interferograms from the measurement channels) may be monitored as the one or more adjustable elements in the beam shaper are sequentially adjusted. In this regard, a configuration of the beam shaper that at least partially compensates for the warp may be selected.

[0026] In some embodiments, the angular profile of the illumination beam directed to the sample is modified based on a predicted amount of sag. For example, as described previously herein, shape deformations such as sag may be predicted based on known properties of the sample and the sample holder. In this regard, a predicted amount or distribution of sag may be used to select the configuration of the beam shaper providing an angular profile of illumination suitable for compensating for the sag.

[0027] Referring now to FIGS. 1A-6, systems and methods for surface profile measurements in the presence of surface warp are described in greater detail in accordance with one or more embodiments of the present disclosure.

[0028] FIG. 1A is a block diagram of a metrology system 100 in accordance with one or more embodiments of the present disclosure. In one embodiment, the metrology system 100 includes a shearing interferometer 102, where the shearing interferometer 102 includes an illumination source 104 to generate an illumination beam 106, a beam shaper 108, and one or more measurement channels 110. The beam shaper 108 may control the spatial and angular profile of the illumination beam 106 directed to a sample 112 and may further collect reflected light (e.g., retroreflected light) from the sample 112 and direct this reflected light to the one or more measurement channels 110. A measurement

channel 110 may include one or more shearing optics to shear the reflected light from the sample 112 into sheared beams along a measurement direction and one or more optical elements to combine the sheared beams on a detector. In this regard, an interferogram (e.g., a shearing interferogram) may be generated on and captured by the detector, where topography information associated with the sample 112 may be represented as variations in the interferogram. In particular, variations in the interferogram may correspond to a profile of the surface slope of the sample 112 along the measurement direction. Surface profile information (e.g., a surface height map) may then be generated by integrating the profile of the surface slope. Further, the metrology system 100 may include multiple measurement channels 110 having different measurement directions to capture full 3D topography information. For example, a metrology system 100 may include two measurement channels 110 with orthogonal measurement directions.

[0029] In another embodiment, the beam shaper 108 includes one or more adjustable optical elements 114. For example, adjusting positions of the one or more adjustable optical elements 114 may provide control of the spatial profile and/or angular profile of the illumination beam 106 on the sample 112. For example, the adjustable optical elements 114 may include, but is not limited to, one or more lenses, one or more field stops, or one or more pupil stops.

[0030] FIG. 1B is a schematic view of the metrology system 100 in accordance with one or more embodiments of the present disclosure.

[0031] The illumination source 104 may include any type of illumination source known in the art suitable for generating a coherent illumination beam 106. In one embodiment, the illumination source 104 includes a laser source configured to generate a laser illumination beam 106. Further, the illumination source 104 may generate an illumination beam 106 having any wavelength or spectrum. However, it is recognized herein that it may be desirable to select a wavelength of the illumination beam 106 based on a composition of the sample 112 to promote reflection and minimize transmission of the illumination beam 106 by the sample 112. In this regard, reflected light captured by the metrology system 100 may include primarily, if not exclusively, light reflected from a top

surface 116 of the sample 112 (e.g., a measurement surface). For example, the illumination source 104 may include, but is not required to include, a helium-neon laser having a wavelength of approximately 633 nm, which may be suitable for use with semiconductor wafers such as, but not limited to, silicon wafers.

[0032] In one embodiment, the metrology system 100 includes a sample mount 117 to secure the sample 112. The sample mount 117 may include any type of mount known in the art suitable for securing the sample 112 in any position or orientation. For example, the sample mount 117 may secure or otherwise support a sample 112 in a horizontal position with three or more contact pins. For instance, a 3-pin sample mount 117 may include three pins upon which the sample 112 rests. By way of another example, the sample mount 117 may secure or otherwise support a sample 112 in a vertical position. For instance, the sample mount 117 may include one or more edge grippers to contact one or more edge points on the sample 112. Further, though not shown, the sample mount 117 may include one or more translation stages such as, but not limited to, linear translation stages, rotational translation stages, or tip/tilt translation stages to position the sample 112 within the metrology system 100 for a measurement.

[0033] In one embodiment, the metrology system 100 includes a beamsplitter 118 configured to receive the illumination beam 106 from the illumination source 104 and transmit at least a portion of the illumination beam 106 along a sample path 120 to the beam shaper 108 and the sample 112. Further, the beamsplitter 118 may receive reflected light 122 from the sample 112 through the beam shaper 108 and direct this reflected light 122 along a measurement path 124 to the one or more measurement channels 110. For example, FIG. 1B illustrates a metrology system 100 having X and Y (e.g., orthogonal) measurement channels 110. As illustrated in FIG. 1B, the metrology system 100 may also include a channel beamsplitter 126 to split the reflected light 122 between the two measurement channels 110 and a turning mirror 128 to fold the optical path of light into a desired form factor.

[0034] Although not shown, the metrology system 100 may include one or more polarization-controlling elements to adjust the polarization of light at any point throughout

the metrology system 100. For example, the illumination beam 106 from the illumination source 104 may be linearly polarized or polarized with a linear polarizer. The beamsplitter 118 may then be configured as a polarizing beamsplitter oriented to pass the illumination beam 106 to the sample 112 with minimal loss. Further, the metrology system 100 may include a quarter-wave plate in the sample path 120 to induce a circular polarization into the illumination beam 106 prior to the sample 112. In this way, the reflected light 122 may be converted into a linearly polarized beam with an orthogonal polarization as the incident illumination beam 106 such that the polarizing beamsplitter 118 may direct the reflected light 122 to the measurement path 124 without loss.

[0035] A measurement channel 110 may include any combination of optical elements suitable for shearing the reflected light 122 along a measurement direction and capturing a shearing interferogram on a detector 130. In one embodiment, a measurement channel 110 includes one or more shearing optics 132 to shear a received portion of the reflected light 122. The shearing optics 132 may include any type of shearing elements known in the art including, but not limited to, one or more Ronchi gratings, a Wollaston prism, or a Nomarski prism. In this regard, the metrology system 100 may operate as any type of shearing interferometer. For example, the two measurement channels 110 in FIG. 1B include two Ronchi gratings 134.

[0036] In one embodiment, the beam shaper 108 includes or is otherwise formed from a beam expander. For example, it may be desirable to expand a diameter of the illumination beam 106 to match the diameter of the sample 112 (or at least a desired measurement area on the sample 112). However, it may not be desirable for the reflected light 122 to have this diameter in the measurement channels 110. Accordingly, the beam shaper 108 may receive the illumination beam 106 at a first diameter 136 suitable for use in the measurement channels 110 and expand the illumination beam 106 to a second diameter 138 suitable for interrogating the sample 112. For example, the illumination beam 106 may be expanded to be approximately a diameter of a wafer. In this case of semiconductor wafers, this diameter may be, but is not required to be, approximately 300 mm or greater. Similarly, the beam shaper 108 may shrink the reflected light 122 from

the sample 112 at the second diameter 138 back down to the first diameter 136 in reverse operation.

[0037] In another embodiment, the metrology system 100 includes an input beam expander 140 to adjust a diameter of the illumination beam 106 from an original diameter 142 provided by the illumination source 104 to the first diameter 136. In this regard, the first diameter 136 and the second diameter 138 may be selected independent of the original diameter 142.

[0038] In one embodiment, the adjustable optical elements 114 include one or more lenses of the beam shaper 108. For example, the beam shaper 108 may include one or more lenses configured to operate as a beam expander/reducer and modifying the positions of one or more of these lenses may adjust the angular profile of the illumination beam 106 as directed to the sample 112. In particular, the lenses of the beam shaper 108 may have a default or nominal position in which the illumination beam 106 enters and exits the beam shaper 108 as a collimated beam (e.g., in a collimated state). In this way, adjustments to the positions of any of the lenses of the beam shaper 108 along the optical axis 144 of the beam shaper 108 may introduce radially symmetric convergence or divergence into the angular profile of the illumination beam 106 directed to the sample 112. Further, adjustments to the positions of any of the lenses of the beam shaper 108 along transverse directions normal to the optical axis 144 may introduce non-symmetric variations into the angular profile of the illumination beam 106. In this regard, more complex angular profiles suitable for more measuring more complex topographies (e.g., saddle shapes, taco shapes, or the like) may be generated.

[0039] In another embodiment, the adjustable optical elements 114 of the beam shaper 108 may include one or more non-focusing optics such as, but not limited to, field stops or pupil stops having selected transmission profiles across the respective planes to further modify the spatial and/or angular distribution of the illumination beam 106 on the sample 112.

[0040] In another embodiment, the beam shaper 108 may include dedicated adjustable optical elements 114. For example, the beam shaper 108 may include a first set of optical

elements for expanding/reducing the beam diameter as described previously herein and a second set of optical elements for adjusting the angular profile of the illumination beam 106 directed to the sample 112.

[0041] Referring now to FIGS. 2A and 2B, the modification of the angular profile of the illumination beam 106 is described in greater detail in accordance with one or more embodiments of the present disclosure.

[0042] In one embodiment, the beam shaper 108 includes a three-lens assembly 202. For example, the beam shaper 108 illustrated in FIGS. 2A and 2B includes a doublet lens 204, a positive meniscus lens 206 and a plano-convex lens 208. However, it is to be understood that the illustration of the specific components of the beam shaper 108 is provided herein solely for illustrative purposes and should not be interpreted as limiting. Rather, the beam shaper 108 may have any number, type, or configuration of lenses suitable for controlling the spatial and/or angular profile of the illumination beam 106 on the sample 112.

[0043] It is contemplated herein that the reflected light 122 from the sample 112 may be collimated (e.g., in a collimated state) when surfaces of the sample 112 lie in a plane orthogonal to the optical axis 144. In this case, the reflected light 122 exiting the beam shaper 108 directed to the measurement channels 110 may also be collimated.

[0044] In one embodiment, the measurement channels 110 are designed to generate an interferogram on the detector 130 when the reflected light 122 is in a collimated state or within an allowable range of deviations from the collimated state. For example, as illustrated in FIG. 2A, the measurement channel 110 may include a pair of Ronchi gratings (e.g., the shearing optics 132), where each Ronchi grating diffracts the reflected light 122 into two or more diffraction orders. Further, the measurement channel 110 may include one or more channel lenses 210 to combine selected diffraction orders from the Ronchi gratings as an interferogram on a sensor 212 of the detector 130. In another embodiment, the measurement channel 110 includes an aperture 214 to pass the selected diffraction orders to the detector 130 and exclude remaining diffraction orders. For example, the

aperture 214 may be located at a Fourier plane relative to shearing optics 132 in which each diffraction order is focused to a discrete portion of the Fourier plane.

[0045] In another embodiment, as illustrated in FIGS. 2A and 2B, the metrology system 100 may include a compensator plate 216 to compensate for optical path length differences in the current measurement channel 110 relative to other measurement channels 110. For example, the compensator plate 216 may compensate for optical path differences associated with the propagation of rays (not shown) through the channel beamsplitter 126 to be directed to another measurement channel 110 (not shown).

[0046] It is further contemplated herein that the reflected light 122 from the sample 112 may deviate from the collimated state when the surfaces of the sample 112 are warped. In this case, the reflected light 122 exiting the beam shaper 108 directed to the measurement channels 110 may also deviate from the collimated state. If the extent of this deviation of the reflected light 122 from a collimated state is too large, then the measurement channels 110 may fail to properly generate an interferogram on the associated detectors or the interferograms may be too distorted to provide reliable measurement data.

[0047] FIG. 2A is a schematic view of the metrology system 100 including a ray diagram of light through the metrology system 100 when configured in a nominal position with a warped sample 112, in accordance with one or more embodiments of the present disclosure. In particular, the sample 112 in FIG. 2A exhibits a bow of -1 mm such that the sample 112 is concave relative to the metrology system 100. Further, multiple diffraction orders of the reflected light 122 from the are shown to illustrate the impact of the warp on the path of light through the metrology system 100. Additionally, FIG. 2A includes optical elements 200 to direct an illumination beam 106 from an illumination source 104 to the beam shaper 108.

[0048] As illustrated in FIG. 2A, the bow in the sample 112 may result in a deviation of the sample 112 from the collimated state. For example, FIG. 2A illustrates the reflected light 122 coming to a focus 218 along the measurement path 124. Further, the bow in the sample 112 may modify the position at which the diffraction orders from the Ronchi

gratings come to a focus (e.g., the position of the Fourier plane). As a result, the aperture 214 may be ineffective at passing the selected diffraction orders. For example, the shifting of the Fourier plane may result in a decrease in the transmission of the selected diffraction orders through the aperture 214 (e.g. due to an increase in the spot size of reflected light 122 at the plane of the aperture 214), which may decrease the contrast of fringes in an interferogram. By way of another example, the shifting of the Fourier plane may allow light from additional diffraction orders to propagate to the detector, which may introduce noise or artifacts into the interferogram.

[0049] FIG. 2B is a schematic view of the metrology system 100 including a ray diagram of light through the metrology system 100 when configured in a modified position with the warped sample 112 of FIG. 2A, in accordance with one or more embodiments of the present disclosure.

[0050] As illustrated in FIG. 2B, one or more lenses of the beam shaper 108 may operate as the adjustable optical elements 114 for modifying the angular profile of the illumination beam 106 directed to the sample 112. In particular, FIG. 2B illustrates a configuration in which the positive meniscus lens 206 is an adjustable optical element 114 and is moved along the optical axis 144 of the beam shaper 108 by 67 mm to compensate for the warp in the sample 112. For example, this adjustment provides that the reflected light 122 exiting the beam shaper 108 is properly collimated. As a result, the aperture 214 may effectively pass the selected diffraction orders to the detector 130. In one embodiment, the aperture 214 and/or the detector 130 of a measurement channel 110 are mounted to a linear translation stage such that the positions of the aperture 214 and/or the detector 130 may be adjusted to compensate for differences in the Fourier plane and/or an imaging plane based on the adjustments of the adjustable optical elements 114. Further, as will be described in greater detail below, the positions of the aperture 214 and/or the detector 130 may be calibrated based on known configurations of the adjustable optical elements 114. In this regard, the positions of the aperture 214 and/or the detector 130 may be adjusted when the configuration of the adjustable optical elements 114 is adjusted.

[0051] It is contemplated herein that the metrology system 100 illustrated in FIGS. 2B and 2C may be suitable for measuring samples 112 having radially-symmetric spherical shapes (e.g., concave or convex shapes) with up to $\pm 1200\ \mu\text{m}$ of bow in a single acquisition cycle. It is to be understood, however, that the particular design of the beam shaper 108 and the particular use of the positive meniscus lens 206 as an adjustable optical element 114 is provided herein solely for illustrative purposes and should not be interpreted as limiting. For example, the beam shaper 108 may have any suitable optical design for controlling the spatial and/or angular profile of the illumination beam 106 on the sample 112. By way of another example, any optical element or combination of optical elements may operate as adjustable optical elements 114 for modifying the angular profile of the illumination beam 106 on the sample 112 to compensate for warping of the sample 112. By way of another example, although FIGS. 2A and 2B illustrate variations of the positions of the adjustable optical elements 114 along the optical axis of the beam shaper 108 to provide for radially symmetric variations of the angular profile of the illumination beam 106 on the sample 112, this description is provided solely for illustrative purposes and should not be interpreted as limiting. Rather, variations of the position of the adjustable optical elements 114 along directions orthogonal to the optical axis of the beam shaper 108 may provide for more complex variations of the angular profile of the illumination beam 106 on the sample 112. In a general sense, the complexity of the beam shaping of the illumination beam 106 directed to the sample 112 may be determined based on the number of degrees of freedom associated with the adjustable optical elements 114.

[0052] Referring again to FIG. 1A, additional components of the metrology system 100 are described in greater detail in accordance with one or more embodiments of the present disclosure.

[0053] In one embodiment, the metrology system 100 includes a controller 146. The controller 146 may include one or more processors 148 configured to execute program instructions maintained on memory 150 (e.g., a memory medium, memory device, or the like). Further, the controller 146 may be communicatively coupled with any of the components of the metrology system 100 including, but not limited to, the beam shaper

108, particular adjustable optical elements 114, or the detectors 130. In this regard, the one or more processors 148 of the controller 146 may execute any of the various process steps described throughout the present disclosure. For example, the one or more processors 148 of the controller 146 may receive measurement signals from the measurement channels 110 (e.g., interferogram data from the detectors 130) and perform one or more analysis steps to extract topography data from the measurement signals. By way of another example, the one or more processors 148 of the controller 146 may generate control signals for the adjustable optical elements to adjust the angular profile of illumination directed to the sample 112. By way of another example, the one or more processors 148 of the controller 146 may select a configuration of the one or more adjustable optical elements 114 suitable for at least partially compensating for warping of the sample 112 and generate suitable control signals to achieve this configuration.

[0054] The one or more processors 148 of a controller 146 may include any processor or processing element known in the art. For the purposes of the present disclosure, the term “processor” or “processing element” may be broadly defined to encompass any device having one or more processing or logic elements (e.g., one or more micro-processor devices, one or more application specific integrated circuit (ASIC) devices, one or more field programmable gate arrays (FPGAs), or one or more digital signal processors (DSPs)). In this sense, the one or more processors 148 may include any device configured to execute algorithms and/or instructions (e.g., program instructions stored in memory). In one embodiment, the one or more processors 148 may be embodied as a desktop computer, mainframe computer system, workstation, image computer, parallel processor, networked computer, or any other computer system configured to execute a program configured to operate or operate in conjunction with the metrology system 100, as described throughout the present disclosure.

[0055] The memory 150 may include any storage medium known in the art suitable for storing program instructions executable by the associated one or more processors 148. For example, the memory 150 may include a non-transitory memory medium. By way of another example, the memory 150 may include, but is not limited to, a read-only memory (ROM), a random-access memory (RAM), a magnetic or optical memory device (e.g.,

disk), a magnetic tape, a solid-state drive and the like. It is further noted that the memory 150 may be housed in a common controller housing with the one or more processors 148. In one embodiment, the memory 150 may be located remotely with respect to the physical location of the one or more processors 148 and the controller 146. For instance, the one or more processors 148 of the controller 146 may access a remote memory (e.g., server), accessible through a network (e.g., internet, intranet and the like).

[0056] In one embodiment, a user interface 152 is communicatively coupled to the controller 146. In one embodiment, the user interface 152 may include, but is not limited to, one or more desktops, laptops, tablets, and the like. In another embodiment, the user interface 152 includes a display used to display data of the metrology system 100 to a user. The display of the user interface 152 may include any display known in the art. For example, the display may include, but is not limited to, a liquid crystal display (LCD), an organic light-emitting diode (OLED) based display, or a CRT display. Those skilled in the art should recognize that any display device capable of integration with a user interface 152 is suitable for implementation in the present disclosure. In another embodiment, a user may input selections and/or instructions responsive to data displayed to the user via a user input device of the user interface 152.

[0057] In another embodiment, the metrology system 100 includes a coarse surface profiler 154 to generate a coarse profile measurement of the sample 112 (e.g., the top surface 116 of the sample 112). For example, the coarse profile measurement may have a larger measurement range than provided by the one or more measurement channels 110. Further, the coarse profile measurement may have a smaller resolution along an axial dimension (e.g., along the optical axis 144 of the beam shaper 108) and/or along a lateral dimension (e.g., orthogonal to the optical axis 144). In this regard, the coarse profile measurement may provide a mapping of any warping of the sample 112 that may be beyond the measurement range of the one or more measurement channels 110.

[0058] As will be described in greater detail below, a coarse profile measurement may be used by the metrology system 100 in various ways. For example, the coarse profile measurement may be used as feed-forward data to determine how to modify the angular

position of the illumination beam 106 on the sample 112 so as to at least partially compensate for warping of the sample 112. By way of another example, the coarse profile measurement may be used to provide an estimation of sample sag based on a geometry of a sample mount (e.g., a three-pin support holder). This sample sag may be, but is not required to be, removed from a surface profile measurement based on interferograms from the measurement channels 110.

[0059] FIG. 3 is a schematic view of a coarse surface profiler 154 in accordance with one or more embodiments of the present disclosure.

[0060] In one embodiment, the coarse surface profiler 154 includes at least one profiling sensor 302. The coarse surface profiler 154 may include any type of profiling sensor 302 known in the art suitable for generating a profile of the topography of the sample 112 including, but not limited to, an interferometric thickness sensor, a confocal distance sensor, or a Shack-Hartmann sensor. In one embodiment, the profiling sensor 302 determines a distance between a reference plate 304. Further, the profiling sensor 302 may measure, but is not required to measure, a thickness of the sample 112. Accordingly, the coarse profile of the top surface 116 of the sample 112 may be directly measured by the profiling sensor 302 or it may be determined based on a measurement of the bottom surface 306 of the sample 112 and a known or assumed thickness 308 of the sample 112. For instance, the thickness 308 of the sample 112 may be, but is not required to be, assumed to be constant across the sample 112.

[0061] The coarse surface profiler 154 may include any number of profiling sensors 302. In one embodiment, as illustrated in FIG. 3, the coarse surface profiler 154 includes a single profiling sensor 302 attached to a translation stage 310. For example, a coarse profile measurement may be generated by scanning the profiling sensor 302 across at least a portion of the sample 112 with a two-dimensional translation stage 310. By way of another example, as illustrated in FIG. 3, a coarse profile measurement may be generated by linearly scanning the profiling sensor 302 with a one-dimensional translation stage 310 and simultaneously rotating the sample 112 with a rotational stage 312. In this way, the coarse profile measurement may have a spiral profile. In another embodiment,

the coarse surface profiler 154 includes two or more profiling sensors 302. For example, the coarse surface profiler 154 may include a two-dimensional array of profiling sensors 302 configured to simultaneously capture a coarse profile measurement. By way of another example, the coarse surface profiler 154 may include a linear array of profiling sensors 302 configured to be scanned across the sample 112 to generate a coarse profile measurement. For instance, the linear array of profiling sensors 302 may be located on a translation stage (not shown) for scanning across the sample 112. In another instance, the sample 112 may be located on a translation stage and scanned through a measurement field of the linear array of profiling sensors 302.

[0062] Additionally, it is contemplated herein that the coarse surface profiler 154 may be integrated into, and thus form a part of, the metrology system 100 as illustrated in FIG. 1A or may be separate and distinct from the metrology system 100. In this regard, the metrology system 100 (e.g., the controller 146 within the metrology system 100) may receive coarse profile measurements from an external source.

[0063] Referring now to FIGS. 4-6, methods for modifying positions of the adjustable optical elements 114 to at least partially compensate for warping of the sample 112.

[0064] FIG. 4 is a flow diagram illustrating steps performed in a metrology method 400 in accordance with one or more embodiments of the present disclosure. Applicant notes that the embodiments and enabling technologies described previously herein in the context of the metrology system 100 should be interpreted to extend to the method 400. It is further noted that the method 400 is not limited to the architecture of the metrology system 100. However, the method steps below are described with reference to the metrology system 100 for illustrative purposes.

[0065] In one embodiment, the method 400 includes a step 402 of placing a sample 112 in a shearing interferometer including a beam shaper 108 with one or more adjustable optical elements 114 configured to direct an illumination beam 106 to the sample 112, where reflected light 122 from the sample 112 is in a collimated state when the one or more adjustable optical elements 114 are in a default configuration and a top surface 116 of the sample 112 is orthogonal to an optical axis 144 of the beam shaper 108. For

example, the shearing interferometer may include, but is not limited to, the metrology system 100 or a portion thereof.

[0066] In another embodiment, the method 400 includes a step 404 of adjusting the configuration of the one or more adjustable optical elements 114 of the beam shaper 108 to provide a selected angular profile of the illumination beam 106 on the sample 112 to at least partially compensate for deviations of the reflected light 122 from the collimated state. The one or more adjustable optical elements 114 may include any type of optical element in the beam shaper 108 such as, but not limited to, one or more lenses, one or more field stops, or one or more pupil stops.

[0067] As described previously herein, deviations of the reflected light 122 from the collimated state may be induced by low-spatial frequency variations in the profile of the top surface 116 of the sample 112 which may be, but are not required to be, caused by warping of the sample 112. Accordingly, step 404 may include adjusting the angular profile of the illumination beam 106 on the sample 112 to at least partially compensate for the deviations of the reflected light 122 from the collimated state.

[0068] In one embodiment, a default configuration of the one or more adjustable optical elements 114 includes default positions (or relative positions) of the one or more adjustable optical elements 114 along the optical axis 144 of the beam shaper 108. Accordingly, the step 404 may include adjusting or otherwise modifying the positions of the adjustable optical elements 114 along the optical axis 144 of the beam shaper 108 relative to the default configuration. For example, modifying a position of one or more lenses of the beam shaper 108 may introduce convergence or divergence into the angular profile of the illumination beam 106 on the sample 112. Additionally, the default configuration may include any selected initial configuration of the adjustable optical elements 114. In one embodiment, the default configuration corresponds to a configuration that provides a collimated illumination beam 106 on the sample 112. In another embodiment, the default configuration corresponds to a configuration expected to at least partially compensate for warping of the sample 112. For example, the default configuration may be selected for a sample 112 based on a coarse profile measurement

from a coarse surface profiler (e.g., coarse surface profiler 154). By way of another example, the default configuration may be selected for a sample 112 based on a measured or estimated sag associated with placement of the sample 112 on a sample holder. In this regard, the default configuration may be different for different samples 112.

[0069] In another embodiment, the method 400 includes a step 406 of generating an output surface profile measurement of the top surface 116 of the sample 112 based on the one or more shearing interferograms.

[0070] It is contemplated herein that a surface profile generated directly from interferograms from the one or more measurement channels 110 may include various artifacts, offsets, and noise. For example, a measured profile ($P_{measured}$) may be characterized as:

$$P_{measured} = P_{actual} + P_{offset}, \quad (1)$$

where P_{actual} is the actual (e.g., physical) surface profile of the sample 112 during a measurement and P_{offset} is an offset distribution associated with systematic offsets, optical aberrations, or modifications of the angular profile of the illumination beam 106 on the sample 112 from a collimated state. Further, although not included in Eq. (1), the measured profile ($P_{measured}$) may include noise (e.g., random noise) associated with a measurement. Accordingly, an output surface profile measurement provided in step 406 (P_{output}) may generally include the measured profile ($P_{measured}$) as well as any corrections to compensate for P_{offset} or a portion thereof.

[0071] Further, a surface profile measurement provided by the controller 146 may include or exclude a sag or bow induced by a sample mount (e.g., a 3-pin sample mount with three contact points) or other support mechanism for securing the sample 112. For example, a sample 112 supported by support points rather than a flat sample mount may generally sag or bow due to gravity. In this regard, the actual surface profile (P_{actual}) during a measurement may be characterized as:

$$P_{actual} = P_{natural} + P_{mount}, \quad (2)$$

where $P_{natural}$ is a natural surface profile of the sample 112 (e.g., free of distortions induced by a sample mount) and P_{mount} is a mount offset distribution associated with distortion of the natural surface profile $P_{natural}$ by the particular sample holder. For example, in the case of a 3-pin sample mount securing a sample 112 in a horizontal position, P_{mount} may correspond to an offset distribution associated with a sag or a bow induced by sample mount.

[0072] In one embodiment, the mount offset distribution (P_{mount}) is removed from the measured surface profile ($P_{measured}$). In this case, the output surface profile (P_{output}) may be written as:

$$P_{output} = P_{measured} - P_{mount}. \quad (3)$$

[0073] The value of P_{mount} may be determined using various techniques. In one embodiment, the mount offset distribution (P_{mount}) is estimated or calculated based on known or measured characteristics of the sample 112 (e.g., composition, size, thickness, shape, a measured coarse surface profile, or the like) and the geometry of the sample holder. For example, the sag may be estimated to scale based on the thickness of the sample 112 by a factor of (thickness)⁻². In another embodiment, the mount offset distribution (P_{mount}) is determined by a coarse surface profile of the sample 112 and thickness measurements received from a coarse surface profiler 154. For example, the coarse surface profiler 154 may simultaneously measure the coarse surface profile and the thickness at various locations on the sample 112 such that the mount-induced distortion of the sample 112 (e.g., sag, bow, or the like) may be directly correlated to a deviation of the sample 112 from flat (excluding patterned features that may be present on a surface of the sample 112). However, it is contemplated herein that the measured deviations of the shape of the sample 112 from flat may not always directly correspond to sag induced by the sample holder. In particular, a contribution of the wafer shape to the mount offset distribution (P_{mount}) may become significant when the out-of-plane deflections or displacements correspond to a significant fraction of the thickness. For instance, in the case of a silicon wafer sample 112 having a 300 mm diameter and a 775 μm thickness that is mounted in a horizontal position on a 3-pin sample mount, when the

wafer bow is 1000 μm , the wafer shape contribution is approximately 8 μm (i.e. the wafer sags 8 μm or $\sim 0.8\%$ less than predictions disregarding wafer shape effects). In one embodiment, the contribution of the wafer shape to the mount offset distribution (P_{mount}) is determined using a look-up table generated prior to a measurement. For example, a look-up table may be generated using finite element analysis based on sample thickness and fit coefficients describing a coarse surface profile of the sample 112 (e.g., associated with a shape of the sample 112 as measured by the coarse surface profiler 154). In this way, the contribution of the wafer shape to the mount offset distribution (P_{mount}) may be estimated with values of thickness and fit coefficients from the coarse surface profiler 154.

[0074] Returning to Eq. (1), an offset distribution (P_{offset}) may include contributions from various sources. For example, the measured profile ($P_{measured}$) may be characterized as:

$$P_{measured} = P_{actual} + P_{offset} = P_{actual} + P_{beam} + P_{aberrations}, \quad (4)$$

where P_{beam} is an induced offset associated with a modification of the angular profile of the illumination beam 106 on the sample 112 from the collimated state and $P_{aberrations}$ is an offset induced by optical aberrations in the illumination beam 106.

[0075] The distribution $P_{aberrations}$ may include systematic offsets caused by optical aberrations associated with a particular configuration of the shearing interferometer 102 including, but not limited to, a particular configuration of the one or more adjustable optical elements 114. This distribution may generally be determinable or estimated such that they may generally be removed from the output surface profile (P_{output}). In this case, the output surface profile (P_{output}) may be written as:

$$P_{output} = P_{measured} - P_{aberrations}. \quad (5)$$

For example, the distribution $P_{aberrations}$ may be at least partially determined by comparing the measured surface profile ($P_{measured}$) generated with different optical configurations.

[0076] Regarding P_{beam} , it is contemplated herein that modifying the angular profile of the illumination beam 106 directed to the sample 112 (e.g., in step 404) may introduce an induced offset distribution (P_{beam}) into the measured surface profile ($P_{measured}$). For example, in the case that the angular profile of the illumination beam 106 is perfectly matched to counteract warping or other variations in the profile of the top surface 116 of the sample 112 and to provide collimated reflected light 122, the shearing interferograms provided by the one or more measurement channels 110 would indicate a surface profile free of the warping. In this regard, a raw surface profile measurement based solely on the interferograms from the one or more measurement channels 110 (e.g., $P_{measured}$) may generally include an induced offset distribution (P_{beam}) based on the angular profile of the illumination beam 106. However, this induced offset distribution (P_{beam}) may be known or otherwise determined based on the selected angular profile of the illumination beam 106 directed to the sample 112 during a measurement. For example, like the offset distribution associated with optical aberrations, the induced offset distribution (P_{beam}) may be at least partially determined by comparing the measured surface profile ($P_{measured}$) generated with different optical configurations.

[0077] Accordingly, the controller 146 may provide a surface profile measurement with or without this induced offset distribution. For example, an output surface profile (P_{output}) may include an unbiased surface profile distribution in which the induced offset distribution (P_{beam}) is removed. In this case, the output surface profile (P_{output}) may be written as:

$$P_{output} = P_{measured} - P_{beam}. \quad (6)$$

[0078] It is further contemplated herein that in the case that the angular profile of the illumination beam 106 is not perfectly matched to the topography of the top surface 116 of the sample 112, the interferograms and the biased surface profile measurement may include residual offsets introduced by the imperfect match. However, in some applications, these residual offsets may be acceptable. Further, in the case that a coarse surface profile measurement is received (e.g., from a coarse surface profiler 154), these

errors may also be determinable and thus removed or otherwise compensated for to provide an accurate depiction of the actual topography of the sample 112.

[0079] Referring again to FIG. 4, it is further contemplated herein that the adjusting the configuration of the one or more adjustable optical elements 114 of the beam shaper 108 (e.g., associated with step 404) may be implemented in a variety of ways.

[0080] For example, a user may manually adjust the one or more adjustable optical elements 114 through the user interface 152 and/or through manual adjustment of the adjustable optical elements 114. Further, the user may utilize any type of data for feedback when adjusting the adjustable optical elements 114 including, but not limited to, one or more shearing interferograms from one or more measurement channels 110, or topographical data from the controller 146 generated based on the shearing interferograms.

[0081] By way of another example, the controller 146 (e.g., through the one or more processors 148) may provide automated or automatic adjustments to the adjustable optical elements 114.

[0082] In one embodiment, the controller 146 determines or estimates low spatial-frequency variations (e.g., warp) of the top surface 116 of the sample 112 based on one or more interferograms received by the measurement channels 110. For example, the controller 146 may generally determine a surface profile measurement or other topographical information (e.g., as in step 406) based on interferograms received from the one or more measurement channels 110. Accordingly, the controller 146 may also determine when a generated surface profile measurement includes residual offsets associated with a deviation of the reflected light 122 from the collimated state. For instance, the controller 146 may identify localized portions of the interferograms or a determined surface profile measurement deviates from other portions. In another instance, the controller 146 may identify low spatial-frequency variations (e.g., warp) in a portion of the interferograms or a determined surface profile measurement. Regardless of the technique, the controller 146 may utilize this information as feedback to modify the angular profile of the illumination beam 106. In some embodiments, the controller 146

may implement a control loop to provide successive changes to the angular profile of the illumination beam 106 to at least partially compensate for deviations of the reflected light 122 from the collimated state.

[0083] In another embodiment, the controller 146 may sequentially adjust the configuration of the adjustable optical elements 114, monitor interferograms or a determined surface profile measurement, and identify a configuration that may at least partially compensate for deviations of the reflected light 122 from the collimated state.

[0084] FIG. 5 is a flow diagram 408 illustrating sub-steps associated with adjusting an angular profile of the illumination beam 106 on the sample 112 in accordance with one or more embodiments of the present disclosure. For example, the sub-steps 408 may be associated with the step 404 of method 400 above.

[0085] In one embodiment, the step 404 includes a sub-step 410 of sequentially adjust the configuration of the one or more adjustable elements to a set of candidate configurations. For example, the set of candidate configurations may represent scanning positions adjustable optical elements 114 individually or in combination. In another embodiment, the step 404 includes a sub-step 412 of monitoring at least one of the one or more shearing interferograms or the output surface profile measurement. Further, monitoring a shearing interferogram may include monitoring the raw interferogram, or any processed version of the interferogram. For example, monitoring a shearing interferogram may include monitoring an associated phase map without or without additional compensations (e.g., as described with respect to FIGS. 6A-6D). In another embodiment, the step 404 includes a sub-step 414 of identifying a configuration of the set of candidate configurations suitable for at least partially compensating for deviations of the reflected light from the collimated state. In another embodiment, the step 404 includes a sub-step 416 of adjusting the configuration of the one or more adjustable optical elements to the identified configuration.

[0086] Referring again to FIG. 4, in another embodiment, the controller 146 may adjust the angular profile of the illumination beam 106 on the sample 112 based on a coarse surface profile measurement (e.g., received from a coarse surface profiler 154). For

example, the step 404 may include receiving a coarse surface profile measurement of the top surface 116 of the sample 112 and adjusting the configuration of the one or more adjustable optical elements 114 of the beam shaper 108 to provide a selected angular profile of the illumination beam 106 directed to the sample 112 to at least partially compensate for deviations of the reflected light 122 from the collimated state based on the coarse surface profile measurement. In this regard, although the coarse surface profile measurement may not have the requisite resolution (either axial or lateral) for a given application, the coarse surface profile measurement may provide sufficient information about the low spatial-frequency variations of the sample 112 (e.g., the warp) to allow the controller 146 to modify the angular profile of the illumination beam 106 on the sample 112 to at least partially compensate for these variations.

[0087] In one embodiment, the controller 146 may adjust the angular profile of the illumination beam 106 on the sample 112 to reduce or minimize a number of fringes on the interferograms or associated phase maps from the one or more measurement channels 110. For example, in a typical analysis, interference fringes represent cycles of 2π in phase. In this way, the intensity variation from dark fringe to bright fringe to dark fringe is one phase cycle and corresponds to a physical quantity. Further, the phase signal derived from intensity images (interference patterns) has cycles of $-\pi$ to $+\pi$. For a smooth, slowly varying, reflective surface with fringe spacing larger than the pixel size, the topographical information of the sample 112 may be recovered through typical phase unwrapping algorithms. However, it is contemplated herein that typical phase unwrapping algorithms may be subject to errors or inconsistencies for cases in which sample 112 includes a patterned surface or is substantially warped. Accordingly, the controller 146 may adjust the angular profile of the illumination beam 106 on the sample 112 to reduce or minimize a number of fringes on the interferograms and thereby reduce or eliminate the number of phase unwrapping steps required to recover the topographical information.

[0088] The controller 146 may utilize any information to modify the angular profile of the illumination beam 106 on the sample 112 such as, but not limited to, a coarse surface profile measurement (e.g., from the coarse surface profiler 154) or a mount offset distribution (P_{mount}).

[0089] The controller 146 may determine the angular profile of the illumination beam 106 on the sample 112 to minimize a number of fringes on the interferograms or associated phase maps, and a corresponding configuration of the one or more adjustable optical elements 114, in various ways.

[0090] In one embodiment, the controller 146 may estimate or predict the interferograms or phase maps associated with one or more configurations of the adjustable optical elements 114. For example, the controller 146 may estimate or predict the interferograms or the associated phase maps associated with one or more configurations of the adjustable optical elements 114. Put another way, the controller 146 may estimate or predict any combination of a measured surface profile ($P_{measured}$), an offset distribution (e.g., P_{offset} , P_{beam} , $P_{aberrations}$, or the like), or mount-induced distortion (P_{mount}). In this regard, the controller 146 may provide any desired output surface profile.

[0091] In some applications, it may not be necessary or desirable perfectly match an angular profile of the illumination beam 106 directed to the sample 112 to the specific topography of the sample 112. For example, it may not be desirable or practical to fully compensate for all possible sample topographies by modifying the configuration of the adjustable optical elements 114 within particular design constraints associated with the beam shaper 108. By way of another example, it may be desirable to balance the benefits of accurately matching an angular profile of the illumination beam 106 directed to the sample 112 to the specific topography of the sample 112 with measurement throughput requirements. Further, as described previously herein, any modification of the angular profile of the illumination beam 106 directed to the sample 112 from the default position may generally result in an induced offset distribution in the resulting surface profile measurement, which may generally be known (e.g., through system calibration) and removed to provide an unbiased surface profile measurement.

[0092] Accordingly, it may not be necessary to fully compensate for all deviations in the reflected light 122 from a collimated state. Rather, in some applications, it may be sufficient to partially compensate for the deviations such that the reflected light 122 is sufficiently collimated to enable the generation of sufficiently accurate or high-contrast

interferograms in the one or more measurement channels 110. In this regard, imperfections associated with an imperfect match between the sample topography and the angular profile of the illumination beam 106 directed to the sample 112 may be compensated for by the controller 146 after the measurement.

[0093] Referring now to FIGS. 6A-6D, reduction of the fringes on phase maps based on interferograms generated by the one or more measurement channels 110 is described in greater detail in accordance with one or more embodiments of the present disclosure.

[0094] FIG. 6A is a phase map 602 along the X direction and a phase map 604 along the Y direction from two measurement channels 110 of a shearing interferometer 102 in accordance with one or more embodiments of the present disclosure. In this example, the phase maps 602,604 in FIG. 6A were generated with a modified angular profile of the illumination beam 106 directed to the sample 112 selected to at least partially compensate for a shape of the sample 112. As seen in FIG. 6A, the phase map 602 along the X direction exhibits two fringes and the phase map 604 along the Y direction exhibits three fringes. Accordingly, the angular profile of the illumination beam 106 is not perfectly matched to the sample 112, but may reduce the number of fringes relative to a collimated illumination beam 106 on the sample 112.

[0095] In one embodiment, the configuration of the adjustable optical elements 114 is selected based on a measured coarse surface profile measurement. This selected configuration may not fully eliminate the fringes in the phase maps 602,604 for various reasons. For example, a coarse surface profiler 154 providing the coarse surface profile measurement may not have the same resolution as the shearing interferometer 102 such that the precise shape of the top surface 116 of the sample 112 may not be known based on the coarse surface profile measurement. By way of another example, it may be impractical to determine the precise configuration of the adjustable optical elements 114 to fully eliminate the fringes. However, as is shown below, full elimination of the fringes based on the modified angular profile of the illumination beam 106 on the sample 112 may not be necessary.

[0096] FIG. 6B is a predicted phase map 606 along the X direction and a predicted phase map 608 along the Y direction associated with the contributions of an offset distribution (e.g., P_{offset}) and a mount-induced distortion (e.g., P_{mount}), in accordance with one or more embodiments of the present disclosure. For example, the phase maps 606,608 in FIG. 6B may correspond to contributions from an induced offset distribution associated with the selected configuration of the adjustable optical elements 114 (P_{beam}), optical aberrations associated with the selected configuration of the adjustable optical elements 114 ($P_{aberrations}$), and mount-induced distortion (P_{mount}).

[0097] FIG. 6C is a compensated phase map 610 along the X direction and a compensated phase map 612 along the Y direction associated with generated by compensating the measured phase maps 602,604 in FIG. 6A with the predicted phase maps 606,608 in FIG. 6B, in accordance with one or more embodiments of the present disclosure. In FIG. 6C, discontinuities associated with fringes are largely, if not completely removed in the compensated phase maps 610,612.

[0098] FIG. 6D is an unwrapped phase map 614 along the X direction and an unwrapped phase map 616 along the Y direction, in accordance with one or more embodiments of the present disclosure. For example, the unwrapped phase maps 614,616 in FIG. 6D may be generated by applying a phase unwrapping technique to the compensated phase maps 610,612 in FIG. 6C. Accordingly, the phase information in the unwrapped phase maps 614,616 may map to topographical information of the top surface 116 of the sample 112 (e.g., surface slope, surface profile, or the like).

[0099] Further, it may be the case that modifying the angular profile of the illumination beam 106 on the sample 112 and/or subsequent processing may render a phase unwrapping step unnecessary in some cases. More generally, reducing the number of discontinuities associated with the phase cycles (and phase variation in general) may simplify the phase unwrapping process and further minimize or reduce potential errors in the phase unwrapping process, which may have the effect of increasing or maximizing the accuracy of the output surface profile measurement.

[00100] Referring again to FIG. 4, the angular profile of the illumination beam 106 directed to the sample 112 may be adjusted by selecting from a set of calibrated angular profiles associated with a set of defined configurations of the adjustable optical elements 114.

[00101] FIG. 7 is a flow diagram illustrating sub-steps 418 associated with adjusting an angular profile of the illumination beam 106 on the sample 112 in accordance with one or more embodiments of the present disclosure. For example, the sub-steps 418 may be associated with the step 404 of method 400 above.

[00102] In one embodiment, the step 404 includes a sub-step 420 of receiving a set of calibrated angular profiles of the illumination beam 106 associated with a set of calibrated configurations of the one or more adjustable optical elements 114 of the beam shaper 108. Further, it may be the case that adjusting the configuration of the one or more adjustable optical elements 114 may require corresponding adjustments to the positions of additional elements in the measurement channels 110 such as, but not limited to, the detector 130 or an aperture 214. In this case, the corresponding adjustments to the positions of the additional elements in the measurement channels 110 may be associated with the set of calibrated configurations in sub-step 420.

[00103] Additionally, the set of calibrated angular profiles of the illumination beam 106 associated with a set of calibrated configurations of the one or more adjustable optical elements 114 of the beam shaper 108 may be generated based on a variety of techniques. For example, the set of calibrated configurations may correspond to systematic variations of one or more adjustable optical elements 114 across a range of positions. By way of another example, at least some of the set of calibrated configurations may correspond to known configurations providing at least partial compensation for sag or bow in the sample 112. For instance, as described previously herein, warping of the sample 112 may be at least partially caused by sag or bow induced by the sample holder. Accordingly, at least some of the set of calibrated configurations may at least partially compensate for known or expected sag or bow of the sample 112.

[00104] In another embodiment, the step 404 includes a sub-step 422 of selecting one angular profile of the set of calibrated angular profiles to at least partially compensate for

deviations of the reflected light 122 from the collimated state. For example, the angular profile of the set of calibrated angular profiles may be, but is not required to be, based on a coarse surface profile measurement as described previously herein. In another embodiment, the step 404 includes a sub-step 424 of adjusting the configuration of the one or more adjustable optical elements 114 to a calibrated configuration of the set of calibrated to provide the selected angular profile. Further, the sub-step 424 may include adjusting the positions of the additional elements in the measurement channels 110 based on the selected calibrated configuration.

[00105] All of the methods described herein may include storing results of one or more steps of the method embodiments in memory. The results may include any of the results described herein and may be stored in any manner known in the art. The memory may include any memory described herein or any other suitable storage medium known in the art. After the results have been stored, the results can be accessed in the memory and used by any of the method or system embodiments described herein, formatted for display to a user, used by another software module, method, or system, and the like. Furthermore, the results may be stored “permanently,” “semi-permanently,” temporarily,” or for some period of time. For example, the memory may be random access memory (RAM), and the results may not necessarily persist indefinitely in the memory.

[00106] It is further contemplated that each of the embodiments of the method described above may include any other step(s) of any other method(s) described herein. In addition, each of the embodiments of the method described above may be performed by any of the systems described herein.

[00107] One skilled in the art will recognize that the herein described components operations, devices, objects, and the discussion accompanying them are used as examples for the sake of conceptual clarity and that various configuration modifications are contemplated. Consequently, as used herein, the specific exemplars set forth and the accompanying discussion are intended to be representative of their more general classes. In general, use of any specific exemplar is intended to be representative of its class, and

the non-inclusion of specific components, operations, devices, and objects should not be taken as limiting.

[00108] As used herein, directional terms such as “top,” “bottom,” “front,” “back,” “over,” “under,” “upper,” “upward,” “lower,” “down,” and “downward” are intended to provide relative positions for purposes of description, and are not intended to designate an absolute frame of reference. Various modifications to the described embodiments will be apparent to those with skill in the art, and the general principles defined herein may be applied to other embodiments.

[00109] With respect to the use of substantially any plural and/or singular terms herein, those having skill in the art can translate from the plural to the singular and/or from the singular to the plural as is appropriate to the context and/or application. The various singular/plural permutations are not expressly set forth herein for sake of clarity.

[00110] The herein described subject matter sometimes illustrates different components contained within, or connected with, other components. It is to be understood that such depicted architectures are merely exemplary, and that in fact many other architectures can be implemented which achieve the same functionality. In a conceptual sense, any arrangement of components to achieve the same functionality is effectively “associated” such that the desired functionality is achieved. Hence, any two components herein combined to achieve a particular functionality can be seen as “associated with” each other such that the desired functionality is achieved, irrespective of architectures or intermedial components. Likewise, any two components so associated can also be viewed as being “connected,” or “coupled,” to each other to achieve the desired functionality, and any two components capable of being so associated can also be viewed as being “couplable,” to each other to achieve the desired functionality. Specific examples of couplable include but are not limited to physically mateable and/or physically interacting components and/or wirelessly interactable and/or wirelessly interacting components and/or logically interacting and/or logically interactable components.

[00111] Furthermore, it is to be understood that the invention is defined by the appended claims. It will be understood by those within the art that, in general, terms used herein,

and especially in the appended claims (e.g., bodies of the appended claims) are generally intended as “open” terms (e.g., the term “including” should be interpreted as “including but not limited to,” the term “having” should be interpreted as “having at least,” the term “includes” should be interpreted as “includes but is not limited to,” and the like). It will be further understood by those within the art that if a specific number of an introduced claim recitation is intended, such an intent will be explicitly recited in the claim, and in the absence of such recitation no such intent is present. For example, as an aid to understanding, the following appended claims may contain usage of the introductory phrases “at least one” and “one or more” to introduce claim recitations. However, the use of such phrases should not be construed to imply that the introduction of a claim recitation by the indefinite articles “a” or “an” limits any particular claim containing such introduced claim recitation to inventions containing only one such recitation, even when the same claim includes the introductory phrases “one or more” or “at least one” and indefinite articles such as “a” or “an” (e.g., “a” and/or “an” should typically be interpreted to mean “at least one” or “one or more”); the same holds true for the use of definite articles used to introduce claim recitations. In addition, even if a specific number of an introduced claim recitation is explicitly recited, those skilled in the art will recognize that such recitation should typically be interpreted to mean at least the recited number (e.g., the bare recitation of “two recitations,” without other modifiers, typically means at least two recitations, or two or more recitations). Furthermore, in those instances where a convention analogous to “at least one of A, B, and C, and the like” is used, in general such a construction is intended in the sense one having skill in the art would understand the convention (e.g., “a system having at least one of A, B, and C” would include but not be limited to systems that have A alone, B alone, C alone, A and B together, A and C together, B and C together, and/or A, B, and C together, and the like). In those instances where a convention analogous to “at least one of A, B, or C, and the like” is used, in general such a construction is intended in the sense one having skill in the art would understand the convention (e.g., “a system having at least one of A, B, or C” would include but not be limited to systems that have A alone, B alone, C alone, A and B together, A and C together, B and C together, and/or A, B, and C together, and the like). It will be further understood by those within the art that virtually any disjunctive word

and/or phrase presenting two or more alternative terms, whether in the description, claims, or drawings, should be understood to contemplate the possibilities of including one of the terms, either of the terms, or both terms. For example, the phrase “A or B” will be understood to include the possibilities of “A” or “B” or “A and B.”

[00112] It is believed that the present disclosure and many of its attendant advantages will be understood by the foregoing description, and it will be apparent that various changes may be made in the form, construction and arrangement of the components without departing from the disclosed subject matter or without sacrificing all of its material advantages. The form described is merely explanatory, and it is the intention of the following claims to encompass and include such changes. Furthermore, it is to be understood that the invention is defined by the appended claims.

CLAIMS

What is claimed:

1. A metrology tool comprising:

- an illumination source configured to generate an illumination beam;
- a beam shaper including one or more adjustable optical elements configured to direct the illumination beam to a sample;
- one or more measurement channels configured to receive reflected light from the sample through the beam shaper and generate one or more shearing interferograms on one or more detectors based on the reflected light, wherein the reflected light is in a collimated state when the one or more adjustable optical elements are in a default configuration and a top surface of the sample is orthogonal to an optical axis of the beam shaper; and
- a controller communicatively coupled to the beam shaper and the one or more measurement channels, wherein the controller includes one or more processors configured to execute program instructions causing the one or more processors to:
 - adjust the configuration of the one or more adjustable optical elements of the beam shaper to provide a selected angular profile of the illumination beam on the sample to at least partially compensate for deviations of the reflected light from the collimated state; and
 - generate an output surface profile measurement of the top surface of the sample based on the one or more shearing interferograms.

2. The metrology tool of claim 1, wherein the output surface profile measurement includes an induced offset distribution associated with the selected angular profile of the illumination beam on the sample.

3. The metrology tool of claim 1, wherein the output surface profile measurement is compensated to remove an induced offset distribution associated with the selected angular profile of the illumination beam on the sample.

4. The metrology tool of claim 1, wherein the one or more processors are further configured to execute program instructions causing the one or more processors to:

determine a mount offset distribution of the sample due to distortion associated with placement of the sample on a sample mount, wherein the output surface profile measurement is compensated to remove the mount offset distribution.

5. The metrology tool of claim 4, wherein determine a mount offset distribution of the sample due to distortion associated with placement of the sample on a sample mount comprises:

calculate the mount offset distribution based on known properties of the sample and known contact points of the sample mount with the sample.

6. The metrology tool of claim 4, wherein determine a mount offset distribution of the sample due to distortion associated with placement of the sample on a sample mount comprises:

determine at least a portion of the mount offset distribution using a lookup table based at least one of a shape or a thickness of the sample and known contact points of the sample mount with the sample.

7. The metrology tool of claim 1, wherein adjust the configuration of the one or more adjustable optical elements of the beam shaper to provide a selected angular profile of the illumination beam on the sample to at least partially compensate for deviations of the reflected light from the collimated state comprises:

receive a coarse surface profile measurement of at least one of the top surface of the sample or a bottom surface of the sample, wherein the coarse surface profile measurement has a larger measurement range than the one or more measurement channels; and

adjust the configuration of the one or more adjustable optical elements of the beam shaper to provide a selected angular profile of the illumination beam on the sample to at least partially compensate for deviations of the reflected light from the collimated state based on the coarse surface profile measurement.

8. The metrology tool of claim 7, wherein adjust the configuration of the one or more adjustable optical elements of the beam shaper to provide a selected angular profile of the illumination beam on the sample to at least partially compensate for deviations of the reflected light from the collimated state based on the coarse surface profile measurement comprises:

receive a set of calibrated angular profiles of the illumination beam associated with a set of calibrated configurations of the one or more adjustable optical elements of the beam shaper;

select one angular profile of the set of calibrated angular profiles to at least partially compensate for deviations of the reflected light from the collimated state based on the coarse surface profile measurement; and

adjust the configuration of the one or more adjustable optical elements to a calibrated configuration of the set of calibrated configurations to provide the selected angular profile.

9. The metrology tool of claim 7, wherein the coarse surface profile measurement is based on a measurement of at least one of a surface profile of the top surface of the sample or a thickness of the sample.

10. The metrology tool of claim 7, wherein the coarse surface profile measurement is based on a measurement of at least one of a surface profile of the bottom surface of the sample or a thickness of the sample.

11. The metrology tool of claim 10, wherein the thickness of the sample is at least one of known, measured, or assumed.

12. The metrology tool of claim 1, wherein adjust the configuration of the one or more adjustable optical elements of the beam shaper to provide a selected angular profile of the illumination beam on the sample to at least partially compensate for deviations of the reflected light from the collimated state comprises:

sequentially adjust the configuration of the one or more adjustable elements to a set of candidate configurations;

monitor at least one of the one or more shearing interferograms or the output surface profile measurement;

identify a configuration of the set of candidate configurations suitable for at least partially compensating for deviations of the reflected light from the collimated state; and

adjust the configuration of the one or more adjustable optical elements to the identified configuration.

13. The metrology tool of claim 1, wherein the configuration of the one or more adjustable optical elements comprises:

positions of the one or more adjustable optical elements along the optical axis of the beam shaper.

14. The metrology tool of claim 1, wherein at least one of the one or more adjustable optical elements comprises:

a lens.

15. The metrology tool of claim 1, wherein at least one of the one or more adjustable optical elements comprises:

at least one of a field stop or a pupil stop.

16. The metrology tool of claim 1, wherein the illumination source is a laser.

17. The metrology tool of claim 16, wherein the laser is a Helium-Neon laser.

18. The metrology tool of claim 1, wherein adjust the configuration of the one or more adjustable optical elements of the beam shaper to provide a selected angular profile of the illumination beam on the sample to at least partially compensate for deviations of the reflected light from the collimated state comprises:

provide one or more control signals to the beam shaper.

19. A metrology tool comprising:

a shearing interferometer comprising:

an illumination source configured to generate an illumination beam;

a beam shaper including one or more adjustable optical elements configured to direct the illumination beam to a sample; and

one or more measurement channels configured to receive reflected light from the sample through the beam shaper and generate one or more shearing interferograms on one or more detectors based on the reflected light, wherein the reflected light is in a collimated state when the one or more adjustable optical elements are in a default configuration and a top surface of the sample is orthogonal to an optical axis of the beam shaper;

a coarse surface profiler including one or more profiling sensors configured to generate a coarse surface profile measurement of the top surface of the sample, wherein the coarse surface profile measurement has a larger measurement range than the one or more measurement channels; and

a controller communicatively coupled to the beam shaper and the one or more measurement channels, wherein the controller includes one or more processors configured to execute program instructions causing the one or more processors to:

adjust the configuration of the one or more adjustable optical elements of the beam shaper to provide a selected angular profile of the illumination beam on the sample to at least partially compensate for deviations of the reflected light from the collimated state based on the coarse surface profile measurement; and

generate an output surface profile measurement of the top surface of the sample based on the one or more shearing interferograms.

20. The metrology tool of claim 19, wherein the one or more profiling sensors comprise:

at least one of an interferometric thickness sensor, a confocal thickness sensor, or a Shack-Hartmann sensor.

21. The metrology tool of claim 19, wherein the sample is mounted to a rotational translation stage, wherein the one or more profiling sensors include one or more profiling sensors mounted to a linear translation stage, wherein one or more profiling sensors provide a plurality of measurements as the sample is rotated on the rotational translation stage and the one or more profiling sensors are translated by the linear translation stage.

22. The metrology tool of claim 19, wherein the coarse surface profiler is integrated into a sample alignment system.

23. The metrology tool of claim 22, wherein the sample is a first test sample, wherein the sample alignment system is configured to operate as a buffer by generating the coarse measurement of the first test sample when an additional test sample is located on the shearing interferometer.

24. The metrology tool of claim 19, wherein adjust the configuration of the one or more adjustable optical elements of the beam shaper to provide a selected angular profile of the illumination beam on the sample to at least partially compensate for deviations of the reflected light from the collimated state comprises:

receive a coarse surface profile measurement of at least one of the top surface of the sample or a bottom surface of the sample, wherein the coarse surface profile measurement has a larger measurement range than the one or more measurement channels; and

adjust the configuration of the one or more adjustable optical elements of the beam shaper to provide a selected angular profile of the illumination beam on the sample to at least partially compensate for deviations of the reflected light from the collimated state based on the coarse surface profile measurement.

25. The metrology tool of claim 24, wherein adjust the configuration of the one or more adjustable optical elements of the beam shaper to provide a selected angular profile of the illumination beam on the sample to at least partially compensate for deviations of the

reflected light from the collimated state based on the coarse surface profile measurement comprises:

- receive a set of calibrated angular profiles of the illumination beam associated with a set of calibrated configurations of the one or more adjustable optical elements of the beam shaper;

- select one angular profile of the set of calibrated angular profiles to at least partially compensate for deviations of the reflected light from the collimated state based on the coarse surface profile measurement; and

- adjust the configuration of the one or more adjustable optical elements to a calibrated configuration of the set of calibrated configurations to provide the selected angular profile.

26. The metrology tool of claim 24, wherein the coarse surface profile measurement is based on a measurement of at least one of a surface profile of the top surface of the sample or a thickness of the sample.

27. The metrology tool of claim 24, wherein the coarse surface profile measurement is based on a measurement of at least one of a surface profile of the bottom surface of the sample or a thickness of the sample.

28. A metrology method comprising:

- measuring a coarse surface profile measurement of a top surface of a sample with a coarse surface profiler;

- placing the sample in a shearing interferometer, wherein the shearing interferometer comprises:

- an illumination source configured to generate an illumination beam;

- a beam shaper including one or more adjustable optical elements configured to direct the illumination beam to the sample;

- one or more measurement channels configured to receive reflected light from the sample through the beam shaper and generate one or more shearing interferograms on one or more detectors based on the reflected

light, wherein the reflected light is in a collimated state when the one or more adjustable optical elements are in a default configuration and the top surface of the sample is orthogonal to an optical axis of the beam shaper;

adjusting the configuration of the one or more adjustable optical elements of the beam shaper to provide a selected angular profile of the illumination beam on the sample to at least partially compensate for deviations of the reflected light from the collimated state based on the coarse surface profile measurement; and

generating a surface profile measurement of the top surface of the sample based on the one or more shearing interferograms.