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SAMPLE INSPECTION WITH MULTIPLE MEASUREMENT MODES

Abstract

An inspection system may include an illumination source configured to generate an illumination beam with multiple wavelengths, an illumination sub-system including one or more illumination optics to direct the illumination beam to a sample at an off-axis angle, and an imaging sub-system. The system may include an objective lens to collect sample light, where the objective lens exhibits chromatic aberration within a spectrum of the illumination beam. The system may include one or more detectors to image the sample. A size of a point spread function (PSF) of the imaging sub-system relative to a pixel size of at least one of the one or more detectors may be adjustable. The system may include a tunable spectral filter with an adjustable linewidth configured to selectively adjust a spectrum of at least one of the illumination beam or the sample light.

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Background/Summary

TECHNICAL FIELD

[0001] The present disclosure relates generally to particle inspection and, more particularly, to dark-field particle inspection with multiple modalities having different illumination linewidths.

BACKGROUND

[0002] Particle detection systems are commonly utilized in semiconductor processing lines to identify defects or particulates on samples (e.g., wafers) which may or may not have films or other structures. In general, detection sensitivity is impacted by parameters of an inspection system such as, but not limited to wavelength or power of illumination. For example, sensitivity may generally improve with increasing power and decreasing wavelength. In some cases, it may be desirable to perform defect inspection using relatively short wavelengths such as, but not limited to, wavelengths in deep ultraviolet (DUV) or vacuum ultraviolet (VUV) spectral regions.

[0003] Achieving high powers at such short wavelengths presents multiple practical challenges. For example, a continuous-wave (CW) laser source providing DUV and/or VUV emission may include a primary laser cavity to generate laser light at a first wavelength and one or more additional resonator cavities to provide frequency conversion of the laser light to reach the desired wavelength. However, such a system may be relatively difficult to manufacture, costly, and sensitive to environmental factors such as temperature fluctuations or vibrations. As another example, a pulsed laser source providing DUV and/or VUV emission may be relatively easier to fabricate and may also be more cost effective. However, pulsed laser sources inherently have larger spectral linewidths than CW laser sources, which may result in chromatic dispersion in an inspection system that may degrade the achievable resolution and/or require costly aberration-corrected optics.

[0004] There is therefore a need to develop systems and methods that mitigate the deficiencies addressed above.

SUMMARY

[0005] In embodiments, the techniques described herein relate to an inspection system including an illumination source configured to generate an illumination beam; an illumination sub-system including one or more illumination optics configured to direct the illumination beam to a sample; an imaging sub-system including an objective lens configured to collect sample light from the sample in response to the illumination beam, where the objective lens exhibits chromatic aberration within a spectrum of the illumination beam; and one or more detectors to image the sample based on at least a portion of the sample light collected by the objective lens, where an image pixel size is adjustable, where the image pixel size is a size of pixels of the one or more detectors projected to a plane of the sample; and a tunable spectral filter with an adjustable linewidth configured to selectively adjust a spectrum of at least one of the illumination beam or the sample light, where the imaging sub-system and the tunable spectral filter are configurable according to at least a first measurement mode and a second measurement mode, where the first measurement mode provides a relatively larger linewidth and a relatively larger image pixel size than the second measurement mode.

[0006] In embodiments, the techniques described herein relate to an inspection system, where the image pixel size is adjustable by controlling a magnification of the imaging sub-system.

[0007] In embodiments, the techniques described herein relate to an inspection system, where the first measurement mode provides a relatively higher chromatic aberration by the objective lens than the second measurement mode.

[0008] In embodiments, the techniques described herein relate to an inspection system, further including a controller communicatively coupled to at least one of the tunable spectral filter or the imaging sub-system, where the controller includes one or more processors configured to execute program instructions causing the one or more processors to receive one or more images of the sample from the one or more detectors; and at least one of identify or characterize one or more defects on the sample based on the one or more images.

[0009] In embodiments, the techniques described herein relate to an inspection system, where the illumination source includes a pulsed laser.

[0010] In embodiments, the techniques described herein relate to an inspection system, where illumination beam includes pulses with temporal pulse widths greater than approximately 1 picometer.

[0011] In embodiments, the techniques described herein relate to an inspection system, where illumination beam includes pulses with temporal pulse widths greater than approximately 10 picometers.

[0012] In embodiments, the techniques described herein relate to an inspection system, where the tunable spectral filter adjusts the spectrum of the illumination beam.

[0013] In embodiments, the techniques described herein relate to an inspection system, where the tunable spectral filter is located within the illumination source.

[0014] In embodiments, the techniques described herein relate to an inspection system, where the tunable spectral filter is located between the illumination source and the sample.

[0015] In embodiments, the techniques described herein relate to an inspection system, where the tunable spectral filter adjusts the spectrum of the sample light.

[0016] In embodiments, the techniques described herein relate to an inspection system, where the spectrum of the illumination beam includes wavelengths in an ultraviolet spectral (UV) range or lower.

[0017] In embodiments, the techniques described herein relate to an inspection system, where the tunable spectral filter includes an etalon.

[0018] In embodiments, the techniques described herein relate to an inspection system, where the tunable spectral filter includes one or more prisms; and a spatial filter.

[0019] In embodiments, the techniques described herein relate to an inspection system, where the tunable spectral filter includes one or more diffraction gratings; and a spatial filter.

[0020] In embodiments, the techniques described herein relate to an inspection system, further including a haze mask when operating in at least the first measurement mode, where the haze mask is configured to pass light scattered from one or more particles on the sample and suppress scattered light from a surface of the sample.

[0021] In embodiments, the techniques described herein relate to an inspection system, where the haze mask includes a waveplate; and a polarizer.

[0022] In embodiments, the techniques described herein relate to an inspection method including generating an illumination beam; directing the illumination beam to a sample; selecting a measurement mode from at least a first measurement mode or a second measurement mode for imaging the sample with an inspection system, where the inspection system includes an imaging sub-system including an objective lens configured to collect sample light from the sample in response to the illumination beam, where the objective lens exhibits chromatic aberration within a spectrum of the illumination beam; and one or more detectors to image the sample based on at least a portion of the sample light collected by the objective lens, where an image pixel size is adjustable, where the image pixel size is a size of pixels of the one or more detectors projected to a plane of the sample, where the inspection system further includes a tunable spectral filter with an adjustable linewidth configured to selectively adjust a spectrum of at least one of the illumination beam or the sample light, where the first measurement mode provides a relatively larger linewidth and a relatively larger image pixel size than the second measurement mode; generating one or more images of the sample using the measurement mode selected from at least the first measurement mode or the second measurement mode; and at least one of identifying or characterizing one or

more defects on the sample based on the one or more images.
[0023] In embodiments, the techniques described herein relate to an inspection system including a controller communicatively coupled to at least one of an illumination source configured to generate an illumination beam, an illumination sub-system including one or more lenses configured to direct the illumination beam to a sample, an imaging sub-system, or a tunable spectral filter, where the imaging sub-system includes an objective lens configured to collect sample light from the sample in response to the illumination beam, where the objective lens exhibits chromatic aberration within a spectrum of the illumination beam; and one or more detectors to image the sample based on at least a portion of the sample light collected by the objective lens, where an image pixel size is adjustable, where the image pixel size is a size of pixels of the one or more detectors projected to a plane of the sample; where the tunable spectral filter provides an adjustable linewidth configured to selectively adjust a spectrum of at least one of the illumination beam or the sample light, where the imaging sub-system and the tunable spectral filter are configurable according to at least a first measurement mode and a second measurement mode, where the first measurement mode provides a relatively larger linewidth and a relatively larger image pixel size than the second measurement mode; and where the controller includes one or more processors configured to execute program instructions causing the one or more processors to receive one or more images of the sample from at least one of the one or more detectors; and at least one of identify or characterize one or more defects on the sample based on the one or more images.
[0024] In embodiments, the techniques described herein relate to an inspection system, where the program instructions are further configured to cause the one or more processors to control at least one of the tunable spectral filter or the imaging sub-system to generate each of the one or more images in a selected measurement mode selected from one or more measurement modes including the first measurement mode and the second measurement mode.
[0025] In embodiments, the techniques described herein relate to an inspection system, where the image pixel size is adjustable by controlling a magnification of the imaging sub-system.
[0026] In embodiments, the techniques described herein relate to an inspection system, where the first measurement mode provides a relatively higher chromatic aberration by the objective lens than the second measurement mode.
[0027] In embodiments, the techniques described herein relate to an inspection system, where the tunable spectral filter adjusts the spectrum of the illumination beam.
[0028] In embodiments, the techniques described herein relate to an inspection system, where the tunable spectral filter adjusts the spectrum of the sample light.
[0029] In embodiments, the techniques described herein relate to an inspection system, where the spectrum of the illumination beam includes wavelengths in an ultraviolet spectral (UV) range or lower.
[0030] 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.

Description

BRIEF DESCRIPTION OF DRAWINGS
[0031] The numerous advantages of the disclosure may be better understood by those skilled in the art by reference to the accompanying figures.
[0032] FIG. **1**A is a block diagram depicting an inspection system, in accordance with one or more embodiments of the present disclosure.

[0033] FIG. **1**B is a simplified schematic depicting an inspection system, in accordance with one or more embodiments of the present disclosure.
[0034] FIG. **1**C is a simplified schematic depicting an inspection system with multiple detectors in different collection paths, in accordance with one or more embodiments of the present disclosure.
[0035] FIG. **1**D is a simplified schematic depicting an inspection system with a tunable spectral filter within the illumination source, in accordance with one or more embodiments of the present disclosure.
[0036] FIG. **1**E is a simplified schematic depicting an inspection system with a tunable spectral filter within an illumination sub-system, in accordance with one or more embodiments of the present disclosure.
[0037] FIG. **1**F is a simplified schematic depicting an inspection system with a tunable spectral filter within a portion of an imaging sub-system common to one or more detectors, in accordance with one or more embodiments of the present disclosure.
[0038] FIG. **1**G is a simplified schematic depicting an inspection system with multiple tunable spectral filters in different collection paths of an imaging sub-system, in accordance with one or more embodiments of the present disclosure.
[0039] FIG. **2**A is a simplified schematic of a tunable spectral filter formed as an etalon, in accordance with one or more embodiments of the present disclosure.
[0040] FIG. **2**B is a schematic diagram depicting spectral modes transmitted by an etalon, in accordance with one or more embodiments of the present disclosure.
[0041] FIG. **2**C is a plot of spectral transmission and reflection by an etalon with length of 0.1 mm and reflective surfaces with a reflectivity of 0.92, in accordance with one or more embodiments of the present disclosure.
[0042] FIG. **2**D is a plot of spectral transmission and reflection by an etalon with length of 0.4 mm and reflective surfaces with a reflectivity of 0.91, in accordance with one or more embodiments of the present disclosure.
[0043] FIG. **2**E is a plot of linewidth (LW) of an etalon as a function of the reflectivity of the reflective surfaces as well as the separation between the reflective surfaces, in accordance with one or more embodiments of the present disclosure.
[0044] FIG. **2**F is a plot of transmissivity of an etalon as a function of the reflectivity of the reflective surfaces as well as the separation between the reflective surfaces, in accordance with one or more embodiments of the present disclosure.
[0045] FIG. **3**A is a simplified schematic of a tunable spectral filter including a dispersive element formed as a prism, in accordance with one or more embodiments of the present disclosure.
[0046] FIG. **3**B is a is a simplified schematic of a tunable spectral filter including a dispersive element formed as a diffraction grating, in accordance with one or more embodiments of the present disclosure.
[0047] FIG. **3**C is a plot depicting the normalized wavelength separation for a prism and a grating in a Littrow configuration, in accordance with one or more embodiments of the present disclosure.
[0048] FIG. **4** is a flow diagram illustrating steps performed in a method for defect inspection, in accordance with one or more embodiments of the present disclosure.

DETAILED DESCRIPTION

[0049] 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.
[0050] Embodiments of the present disclosure are directed to systems and methods providing cost-effective image-based optical inspection using multiple selectable measurement configurations,

which are referred to herein as measurement modes. In embodiments, an inspection system includes an illumination source providing a pulsed laser illumination beam with multiple longitudinal modes and a tunable spectral filter that may selectively control a linewidth (and therefore a power) of the illumination beam. For example, the illumination source may include a high-power pulsed laser. The inspection system may further be configurable according to two or more configurations (e.g., measurement modes) providing different combinations of the linewidth and power of the illumination beam, an image pixel size (e.g., a size of pixels of a detector projected to a sample plane), or an imaging magnification. In this way, different optical modes may be tailored for different sample types and/or applications in which different sources of noise dominate.

[0051] Embodiments of the present disclosure may provide robust operation using relatively cost-effective components. For example, embodiments of the present disclosure may utilize a high-power pulsed laser, which may be a more cost-effective and/or robust way to achieve high powers than using a CW laser. Embodiments of the present disclosure may further use any objective lens including, but not limited to, an objective lens that is weakly corrected or uncorrected for chromatic aberration over the available linewidth of the illumination beam (e.g., an uncorrected or weakly corrected objective lens that exhibits fully formed or minor residual chromatic aberration). It is contemplated herein that it is significantly more expensive to correct chromatic aberration in a high numerical aperture (NA) lens in a deep ultraviolet (UV) wavelength range than for a visible wavelength range. Notably, the image pixel size may be adjusted in combination with the illumination linewidth based on the relevant noise sources to provide high signal to noise ratios (SNRs) in a wide range of applications or sample types. In embodiments, an inspection system may be configured to operate in at least two measurement configurations, where a first measurement configuration is tailored for situations in which sensor noise is dominant and a second configuration is tailored for situations in which optical noise associated with surface scattering (e.g., surface haze) is dominant. The first configuration may be suitable for samples with low surface haze is either negligible (e.g., for well-polished samples such as semiconductor wafers) or suppressed by the inspection system and is thus referred to herein as a low-haze configuration. In such a low haze configuration, higher laser power and larger image pixel size tends to provide higher SNR. Further, relatively larger image pixel sizes can tolerate more chromatic aberration. As a result, a tunable spectral filter can be wider or fully open to provide maximum power for illumination. The second configuration may be suitable for samples with relatively higher surface haze (e.g., for samples with one or more deposited films). In such a haze-limited configuration (e.g., a high-haze configuration), relatively smaller image pixel sizes improve SNR. However, relatively smaller image pixel sizes provide lower tolerance of spectral line width such that the spectral line width needs to be narrowed (e.g., using a tunable spectral filter) to achieve higher SNR. The loss of laser power due to the narrower spectral filter with smaller image pixel size has much less impact on SNR. The spectral line width can be further optimized for cases in between sensor noise limited cases and haze limited cases.

[0052] Referring now to FIGS. **1**A-**4**, systems and methods providing sensitive optical inspection with multiple selectable measurement configurations are described in greater detail, in accordance with one or more embodiments of the present disclosure.

[0053] FIG. **1**A is a block diagram depicting an inspection system **100**, in accordance with one or more embodiments of the present disclosure. In embodiments, the inspection system **100** includes an illumination source **102** to generate an illumination beam **104**, and an illumination sub-system **106** including one or more illumination optics **108** to direct the illumination beam **104** to a sample **110**. The inspection system **100** may also include an imaging sub-system **112** with at least an objective lens **114** to image the sample **110** with a based on light emanating from the sample **110**, which is referred to herein as sample light **116**. For example, the imaging sub-system **112** may include one or more detectors **118** to generate images of the sample **110** (e.g., an illuminated portion thereof) based on the sample light **116**. In embodiments, the inspection system **100** further includes a tunable spectral filter **120** to control a spectral linewidth associated with a spectrum of light used to generate images of the sample **110** (e.g., an imaging linewidth). For example, the tunable spectral filter **120** may control a linewidth of the illumination beam **104** (e.g., an illumination linewidth) and/or a linewidth of the sample light **116** directed to a detector **118** for imaging. In this way, a tunable spectral filter **120** may be located in an illumination sub-system **106** and/or an imaging sub-system **112** of the inspection system **100**.

[0054] In embodiments, as illustrated in FIG. **1**B, the inspection system **100** is a dark-field imaging system configured to exclude specularly-reflected light during imaging. In this regard, the inspection system **100** may image the sample **110** based primarily on scattered or diffracted light. Dark-field imaging may be implemented using any technique known in the art. For example, FIG. **1**B illustrates a configuration in which the illumination sub-system **106** includes illumination optics **108** arranged to direct the illumination beam **104** to the sample **110** at an oblique incidence angle that is excluded from a NA of an objective lens **114** used to collect sample light **116** for imaging. In this way, specular reflection of the illumination beam **104** may also be excluded from the NA of the objective lens **114** and not collected. The oblique incidence angle may generally include any selected incidence angle. For example, the incidence angle may be, but is not required to be, greater than 60 degrees with respect to a surface normal. As another example, though not shown, the illumination sub-system **106** may direct the illumination beam **104** to the sample **110** through the objective lens **114** and may further include one or more beam blocks or apertures to prevent specular reflection of the illumination beam **104** from reaching a detector **118**. It is noted that the inspection system **100** is not limited to dark-field imaging and may implement bright-field imaging or any other suitable imaging technique. In this way, the inspection system **100** may be configured as any type of imaging system known in the art. Further, the objective lens **114** may have, but is not required to have, a NA of approximately 0.9 or greater. In embodiments, the inspection system **100** may include one or more components to block specular reflection from reaching the detector **118**.

[0055] In embodiments, the inspection system **100** further includes a controller **122** including one or more processors **124** configured to execute program instructions maintained on a memory **126** (e.g., memory medium). The controller **122** may be communicatively coupled to any components of the inspection system **100** such as, but not limited to, the tunable spectral filter **120** or detectors **118**. For example, the controller **122** may receive data from any components of the inspection system **100** and/or direct, via control signals, any components of the inspection system **100** to perform various actions. In this way, the program instructions may cause the processors **124** to implement and/or direct the implementation of any of the process steps within the present disclosure. For example, the controller **122** may control or otherwise direct (e.g., via control signals) components such as, but not limited to, the tunable spectral filter **120** or detectors **118** to generate images of a sample **110** using selected imaging parameters. As another example, the controller **122** may receive, analyze, and/or process images of the sample **110** generated by a detector **118**. As another example, the controller **122** may identify and/or characterize defects on the sample **110**.

[0056] The inspection system **100** identify and/or characterize any type of defects on any type of sample **110**, which is broadly referred to herein as inspection. In embodiments, the inspection system **100** can identify and/or characterize defects on samples **110** associated with semiconductor fabrication processes. For example, a sample **110** may include, but is not limited to, an unprocessed (e.g., bare) semiconductor wafer, a semiconductor wafer having one or more films, or a semiconductor wafer having one or more patterned features (e.g., patterned films). In this configuration, defects of interest may include, but are not limited to, particles on the sample **110** or structural damage to the sample **110** in the form of scratches, dents, pits, or the like.

[0057] In many applications, defects are smaller than the optical resolution of imaging sub-system **112** such that an image of such defects corresponds to a PSF of the imaging system altered by the electric field distribution of light scattered by the defect and/or the sample **110**. In particular, the PSF of the imaging sub-system **112** describes the distribution of light associated with a point object (e.g., an infinitely small object), which is governed by diffraction of light throughout the imaging sub-system **112**. Further, the PSF may be defined or otherwise characterized at the plane of the sample **110**.

[0058] Inspection sensitivity may be based at least in part on a SNR associated with a defect signal measured by pixels of a detector **118** as well as various noise sources. For example, a source of noise may include optical scattering noise associated with scattering of the illumination beam **104** by the sample (e.g., surface haze) and/or air molecules near an imaging field. As another example, a source of noise may include sensor noise such as, but not limited to, dark current noise or readout noise.

[0059] It is contemplated herein that noise sources may vary widely for different types of samples **110** and/or applications. For example, surface haze may be substantially lower for well-polished samples **110** (e.g., bare semiconductor wafers, or the like) than for samples **110** with one or more deposited films or other features.

[0060] It is further contemplated herein that different techniques may be utilized to improve SNR depending on which source of noise is dominant for a particular application. In embodiments, the inspection system **100** is configurable to operate in two or more different measurement configurations. In this way, the inspection system **100** may be tailored to provide a high SNR in the presence of different dominant noise sources.

[0061] Each measurement configuration may correspond to a unique set of parameters of the inspection system **100** such as, but not limited to, a spectral linewidth (e.g., a linewidth of the illumination beam **104** and/or collected sample light **116**) or an image pixel size of a detector **118**. The image pixel size refers to a size of a pixel of the detector **118** (e.g., a sensor pixel size) projected to a plane of the sample **110**, which may correspond to the sensor pixel size divided by the optical magnification of the imaging sub-system **112**. In this way, the image pixel size may be determined by the sensor pixel size and the optical magnification of the imaging sub-system **112**. It is contemplated herein that limiting the spectral linewidth may reduce the signal strength, but may also limit chromatic aberration by the objective lens **114** or other components. In this way, the spectral linewidth and the image pixel size may be balanced to provide different measurement modes suitable for different imaging and/or sample conditions such as, but not limited to, an amount of surface haze.

[0062] Non-limiting examples of measurement configurations of the inspection system **100** are now described in greater detail, in accordance with one or more embodiments of the present disclosure.

[0063] In embodiments, the inspection system **100** may be configured to operate in a low-haze configuration (e.g., a first measurement configuration) tailored for applications in which noise associated with surface haze from the sample **110** is sufficiently low that sensor noise is dominant during imaging. For example, surface haze may naturally be low and/or may be effectively suppressed for well-polished samples **110** such that sensor noise may dominate. The suppression of surface haze in defect inspection is described generally in U.S. Pat. No. 10,942,135 issued on Mar. 9, 2021 and U.S. Pat. No. 10,948,423 issued on Mar. 16, 2021, both of which are incorporated herein by reference in their entireties. For example, the inspection system **100** may include a haze mask that passes light scattered from one or more particles (e.g., defects) on the sample **110** and suppresses scattered light from a surface of the sample **110** (e.g., surface haze). The haze mask may suppress the surface haze using any technique including, but not limited to, directing the surface haze along a different optical path than remaining sample light **116** or absorbing the surface haze. As an illustration, a haze mask may include, but is not limited to, one or more polarization rotating optics (e.g., one or more waveplates), and/or one or more polarizers arranged to distinguish surface haze from defect signals.

[0064] When sensor noise is dominant, the SNR associated with an imaged defect may scale with increasing illumination power and/or increasing image pixel size relative to the PSF to capture a greater percentage of the signal per pixel. Further, sensor noise may be fixed or known for a particular sensor and associated operating conditions (e.g., temperature, or the like) and is typically not dependent on (or only weakly dependent on) the sensor pixel size.
[0065] Beneficially, this configuration may be tolerant to chromatic aberrations from the objective lens **114** or other components associated with the wide spectral linewidth. For example, chromatic aberrations may manifest as an increase of the size and/or decrease of the peak power of the imaged defect (e.g., the PSF). However, the image pixel size may be selected to capture a relatively large portion of the PSF or in some cases all of the PSF even in the presence of chromatic aberration to maintain a high SNR. As a result, an uncorrected or weakly corrected objective lens **114** may be used. Since an uncorrected or weakly corrected objective lens **114** may be substantially less expensive than a corrected objective lens **114**, particularly when corrected for UV wavelengths, this may substantially reduce the cost of the inspection system **100**.
[0066] In embodiments, the inspection system **100** may be configured to operate in a high-haze configuration (e.g., a second measurement configuration) tailored for applications in which noise associated with surface haze from the sample **110** dominates sensor noise. This may be the case for samples including deposited films or other features.
[0067] When noise associated with surface haze is dominant, the SNR regime may not scale (or may scale only weakly) with increasing illumination power since both the signal and the noise depend on the illumination power. Instead, the SNR may be improved by decreasing the image pixel size (or decreasing magnification of the imaging sub-system **112**) since optical noise associated with surface haze may be distributed across an image plane and smaller image pixel size captures less of this noise per pixel. It is understood that this scaling may plateau when the pixel size becomes much smaller than the PSF. It may also be desirable to provide a diffraction-limited PSF (or more generally to provide relatively small PSF with a high peak) to improve the signal strength captured by the smaller pixels. For example, the PSF may be improved by limiting the spectral linewidth (e.g., with the tunable spectral filter **120**) to reduce chromatic aberration by the objective lens **114** or other components. As an illustration, the tunable spectral filter **120** may limit the PSF to be diffraction-limited (e.g., limited by diffraction in the imaging sub-system **112**). As another illustration, the tunable spectral filter **120** may limit the PSF to be smaller than or equal to the image pixel size.
[0068] It is contemplated herein that the low-haze and high-haze configurations described herein do not require particular values of the various parameters of the inspection system **100** but may rather provide relative changes of these parameters. For example, a high-haze configuration may provide smaller image pixel size and/or higher magnification than a low-haze configuration. As another example, a high-haze configuration may provide a relatively lower spectral linewidth than a low-haze configuration.
[0069] Further, the descriptions of the low-haze configuration and the high-haze configuration are provided solely for illustrative purposes and should not be interpreted as limiting on the scope of the present disclosure. Rather, the inspection system **100** may be configured to operate in any number of measurement configurations with any combination of parameters.
[0070] Referring now to FIGS. **1**B-**1**G, the implementation of multiple measurement modes in optical inspection is described in greater detail, in accordance with one or more embodiments of the present disclosure. In particular, FIG. **1**B depicts an inspection system **100** generally, whereas FIGS. **1**C-**1**G, depict various non-limiting configurations of an inspection system **100** providing multiple measurement modes.
[0071] FIG. **1**B is a simplified schematic depicting an inspection system **100**, in accordance with one or more embodiments of the present disclosure.
[0072] As described with respect to FIG. **1**A, the inspection system **100** may include an

illumination source **102** configured to generate an illumination beam **104**, an illumination sub-system **106** with illumination optics **108** configured to direct the illumination beam **104** to the sample **110**, and an imaging sub-system **112** with at least an objective lens **114** to collect sample light **116** and generate an image of the sample **110** on one or more detectors **118**.

[0073] The illumination beam **104** may include one or more selected wavelengths of light including, but not limited to, ultraviolet (UV) radiation, visible radiation, or infrared (IR) radiation. For example, the illumination source **102** may provide, but is not required to provide, an illumination beam **104** having wavelengths shorter than approximately 350 nm. By way of another example, the illumination beam **104** may provide a wavelength of approximately 266 nm. By way of another example, the illumination beam **104** may provide a wavelength of approximately 213 nm. By way of another example, the illumination beam **104** may provide a wavelength of approximately 193 nm. It is recognized herein that imaging resolution and light scattering by small particles (e.g., relative to the wavelength of the illumination beam **104**) both generally scale inversely with wavelength such that decreasing the wavelength of the illumination beam **104** may generally increase the imaging resolution and scattering signal from the small particles. Accordingly, illumination beam **104** may include short-wavelength light including, but not limited to, extreme ultraviolet (EUV) light, deep ultraviolet (DUV) light, or vacuum ultraviolet (VUV) light.

[0074] The illumination beam **104** may further have any temporal profile. For example, the illumination beam **104** may have a continuous temporal profile, a modulated temporal profile, a pulsed temporal profile, or the like.

[0075] The illumination source **102** may include any type of light source known in the art. In embodiments, the illumination source **102** is pulsed laser source (e.g., a high-power pulsed laser) providing an illumination beam **104** with multiple longitudinal modes. For example, the illumination source **102** may include, but is not required to include, a high-power pulsed laser providing power in a range of 1-100 W. In the case of a pulsed laser illumination source **102**, a linewidth of the illumination beam **104** (sample light **116** associated with the illumination beam **104**) may be tuned with the tunable spectral filter **120**. For example, the linewidth of the illumination beam **104** may be greater than approximately one picometer. As another example, the linewidth of the illumination beam **104** may be greater than approximately 10 picometers. For example, the linewidth of the illumination beam **104** may be greater than approximately one nanometer. As another example, the linewidth of the illumination beam **104** may be sufficiently large to induce chromatic dispersion in a selected objective lens **114** used to collect sample light **116**. As an illustration, it may be desirable to use an objective lens **114** that is either uncorrected for or only weakly corrected for chromatic aberration for wavelengths associated with the illumination beam **104**. Such an objective lens **114** may reduce cost relative to a better-corrected version. In this case, the chromatic aberration may manifest as a degradation of a PSF at a detector **118** when a full linewidth of the illumination beam **104** is used such as, but not limited to, a decrease of peak amplitude of the PSF beyond a tolerance or an increase of a size of the PSF beyond a tolerance. As described throughout the present disclosure, a tunable spectral filter **120** may control an effective linewidth of light used for imaging (e.g., control a linewidth of the illumination beam **104** and/or the sample light **116** reaching a detector **118**) and thus control the amount of degradation of the PSF due to chromatic aberration. In this way, different measurement modes may utilize different linewidths of light for imaging.

[0076] The illumination optics **108** in the illumination sub-system **106** may include any number of components to direct or otherwise manipulate the illumination beam **104**. For example, the illumination optics **108** may include one or more illumination lenses **128** to focus and/or relay the illumination beam **104**. The illumination lenses **128** may further provide any number of relayed illumination pupil planes and/or illumination field planes. As another example, the illumination optics **108** may include one or more illumination beam-controlling optics **130** such as, but not limited to apodizers, polarizers, spectral filters, neutral density filters, or homogenizers. Further, the illumination beam-controlling optics **130** may be located at any suitable location such as, but not limited to, an illumination pupil plane or an illumination field plane.

[0077] It is recognized herein that the strength of surface haze may depend on multiple factors including, but not limited to incidence angle or polarization of the illumination beam **104**. For example, the strength of surface haze may be relatively high for near-normal angles of incidence and may drop off for higher incidence angles. In embodiments, the illumination sub-system **106** directs (e.g., via the illumination lenses **128** or other suitable elements), the illumination beam **104** to the sample **110** at an oblique incidence angle to increase a defect signal (e.g. a strength of sample light **116** associated with a defect on the sample **110**). The oblique incidence angle may generally include any selected incidence angle. For example, the incidence angle may be, but is not required to be, greater than 60 degrees with respect to a surface normal of the sample **110**. However, this is not a limitation and the illumination beam **104** may be directed to the sample **110** at any incidence angle.

[0078] The imaging sub-system **112** may include an objective lens **114** to collect sample light **116** from the sample **110** in response to illumination with the illumination beam **104** and may further include any number of generating one or more images of the sample **110** with at least a portion of the sample light **116**.

[0079] The imaging sub-system **112** may include any number of imaging beam-conditioning optics **132** to direct and/or modify the sample light **116** including, but not limited to, one or more lenses, one or more filters, one or more apertures, one or more polarizers, or one or more phase plates.

[0080] The imaging sub-system **112** may include any number of lenses **134** to manipulate the sample light **116** collected by the objective lens **114**. For example, the lenses **134** may operate with the objective lens **114** to generate an image of the sample **110** on a detector **118**. As another example, the lenses **134** may relay one or more planes (e.g., relay one or more pupil planes **136** and/or field planes **138**), which may allow for further manipulation of the sample light **116** with the imaging beam-conditioning optics **132**.

[0081] In one embodiment, as illustrated in FIG. **1**B, the imaging sub-system **112** includes one or more imaging beam-conditioning optics **132** located at or near a pupil plane **136**. For example, the imaging sub-system **112** may include imaging beam-conditioning optics **132** configured to suppress surface haze from reaching a detector **118** such as, but not limited to, a haze-rejection polarizer (e.g., a radial polarizer, or the like) or a phase mask at or near a pupil plane **136**. In this regard, the inspection system **100** may control and adjust selected aspects of the sample light **116** used to generate an image on the detector **118** including, but not limited to, the intensity, phase, and polarization of the sample light **116** as a function of scattering angle and/or position on the sample **110**.

[0082] In embodiments, as illustrated in FIG. **1**B, the imaging sub-system **112** includes one or more imaging beam-conditioning optics **132** located at or near a pupil plane **136**. For example, the imaging sub-system **112** may include imaging beam-conditioning optics **132** such as, but not limited to, a haze mask configured to suppress surface haze from the sample **110**. As an illustration, a haze mask may include components such as, but not limited to, polarization-manipulation optics (e.g., polarization rotator, waveplates, polarizers or the like) or phase masks. As another example, the imaging sub-system **112** may include one or more apertures or beam blockers to prevent specular reflection or other unwanted light from reaching a detector **118**. In a general sense, imaging beam-conditioning optics **132** may be used to manipulate any combination of the intensity, phase, or polarization of the sample light **116**.

[0083] However, it is recognized herein that a limited number of imaging beam-conditioning optics **132** may be placed at a particular pupil plane **136** or sufficiently near a particular pupil plane **136** to provide a desired effect. Accordingly, for the purposes of the present disclosure, reference to one or more elements at a pupil plane **136** may generally describe one or more elements at or sufficiently close to a pupil plane **136** to produce a desired effect. In some embodiments, though not shown, the imaging sub-system **112** may include additional lenses to generate one or more additional pupil planes **136** such that any number of imaging beam-conditioning optics **132** may be placed at or near a pupil plane **136**.

[0084] A detector **118** may include any type of sensor known in the art suitable for measuring illumination received from the sample **110**. For example, a detector **118** may include a multi-pixel detector suitable for capturing an image of the sample **110** such as, but not limited to, a charge-coupled device (CCD) detector, a complementary metal-oxide-semiconductor (CMOS) detector, a time-delayed integration (TDI) detector, a photomultiplier tube (PMT) array, an avalanche photodiode (APD) array, or the like. In embodiments, a detector **118** includes a spectroscopic detector suitable for identifying wavelengths of the sample light **116**.

[0085] The imaging sub-system **112** may generally include any number of detector **118**.

[0086] FIG. **1**C is a simplified schematic depicting an inspection system **100** with multiple detectors **118***a,b* in different collection paths **140***a,b*, in accordance with one or more embodiments of the present disclosure. For example, the imaging sub-system **112** may include one or more beamsplitters **142** to split the sample light **116** collected by the objective lens **114** into any number of collection paths **140** (e.g., the collection paths **140***a,b* here). The imaging sub-system **112** may then include one or more detectors **118** within each collection path **140**. Any or all of the collection paths **140** may further include any combination of components suitable for imaging the sample **110** such as, but not limited to, imaging beam-conditioning optics **132** or lenses **134**.

[0087] The imaging sub-system **112** may further include any component or combination of components suitable for selectively directing the sample light **116** collected by the objective lens **114** to a selected collection path **140** such as, but not limited to, one or more shutters or one or more polarization-controlling optics (e.g., polarization rotators, polarizing beamsplitters, or the like). For example, FIG. **1**C depicts a non-limiting configuration including shutters **144** in the collection paths **140**, which may be coupled to the controller **122** for automated control (e.g., via control signals) or may be manually operated (e.g., by a user).

[0088] Such a configuration may be also suitable for polarization-based haze-suppression techniques in which one sub-path provides an image of the sample **110** with suppressed surface haze and another sub-path provides an image of the surface haze. For instance, such a configuration may be suitable for, but is not limited to, implementing polarization-based haze-suppression techniques described in U.S. Pat. Nos. 10,942,135 and 10,948,423 referenced above and incorporated herein by reference in their entireties. For example, the surface haze may be at least substantially directed along one path to a first detector **118***a*, while the remaining sample light **116** (e.g., primarily including light associated with defects) may be directed to a second detector **118***b*.

[0089] As another example, though not shown, a collection path **140** may include one or more additional beamsplitters to split sample light **116** along additional sub-paths to multiple detectors **118**.

[0090] As another example, the inspection system **100** may include different detectors **118** having different sensor pixel sizes. For example, the first detector **118***a* and the second detector **118***b* may have different sensor pixel sizes, which may provide different available image pixel sizes.

[0091] In embodiments, the inspection system **100** includes at least one tunable spectral filter **120** to selectively control a linewidth of light used to image a sample **110**. A tunable spectral filter **120** may be located at any location of the inspection system **100** including, but not limited to, within the illumination source **102**, within the illumination sub-system **106**, or within the imaging sub-system **112**.

[0092] Referring now to FIGS. **1**B-**1**G, various non-limiting configurations of an inspection system **100** providing multiple measurement modes are shown, in accordance with one or more embodiments of the present disclosure.

[0093] As described previously herein, a measurement mode of an inspection system **100** may include a unique combination of linewidth of light used for imaging and an image pixel size. Put another way, a measurement mode of an inspection system **100** may include a unique combination of linewidth of light used for imaging (e.g., a spectral linewidth) and an image pixel size. Put another way, a measurement mode may include a unique combination of linewidth of light used for imaging and a relationship between image pixel size and PSF size (e.g., a size of a diffraction-limited defect).

[0094] The spectral linewidth and/or the image pixel size may be adjusted or otherwise controlled using any technique known in the art.

[0095] For example, the image pixel size may be adjusted by controlling an optical magnification of the imaging sub-system **112**. As an illustration, the imaging sub-system **112** may include one or more zoom lenses and/or lenses with adjustable positions suitable for adjusting the imaging magnification. For instance, any of the lenses **134** in FIG. **1**B or **1**C may be implemented as zoom lenses and/or lenses with adjustable positions such that the image pixel size may be adjusted or otherwise controlled. As another example, the imaging sub-system **112** may include multiple detectors **118** having different pixel sizes that may be selectively used for imaging. In this way, different measurement modes may selectively utilize different detectors **118** to achieve different pixel sizes. Any suitable technique may be used to select between multiple available detectors **118** when imaging in a particular measurement mode.

[0096] As another example, the spectral linewidth may be adjusted by a tunable spectral filter **120** placed at any location suitable for adjusting a linewidth of the illumination beam **104** and/or the sample light **116**. FIGS. **1**D-**1**G depict a tunable spectral filter **120** within various non-limiting locations of an inspection system **100**. FIGS. **1**D-**1**G depict a configuration of the inspection system **100** shown in FIG. **1**C. However, this is merely illustrative and should not be interpreted as limiting the scope of the present disclosure. Rather, a tunable spectral filter **120** may be included in any suitable location within any configuration of an inspection system **100** including, but not limited to, the configuration depicted in FIG. **1**B.

[0097] FIG. **1**D is a simplified schematic depicting an inspection system **100** with a tunable spectral filter **120** within the illumination source **102**, in accordance with one or more embodiments of the present disclosure. In this configuration, the tunable spectral filter **120** may directly control a spectrum of the illumination beam **104**.

[0098] FIG. **1**E is a simplified schematic depicting an inspection system **100** with a tunable spectral filter **120** within an illumination sub-system **106**, in accordance with one or more embodiments of the present disclosure. In this configuration, the tunable spectral filter **120** may pass any selected portion of the spectrum of the illumination beam **104**.

[0099] FIG. **1**F is a simplified schematic depicting an inspection system **100** with a tunable spectral filter **120** within a portion of an imaging sub-system **112** common to one or more detectors **118**, in accordance with one or more embodiments of the present disclosure. In this configuration, the tunable spectral filter **120** may pass any selected portion of the spectrum of the sample light **116** collected by the objective lens **114**.

[0100] FIG. **1**G is a simplified schematic depicting an inspection system **100** with multiple tunable spectral filters **120** in different collection paths **140** of an imaging sub-system **112**, in accordance with one or more embodiments of the present disclosure. In this configuration, any particular tunable spectral filter **120** may pass a selected portion of the spectrum of sample light **116** within the associated collection path **140**. In this way, the spectrum of the sample light **116** used to generate an image of the sample **110** may be tailored for each detector **118**. For instance, the spectrum of the sample light **116** used to generate an image of the sample **110** may be tailored to provide a selected size of a PSF relative to the image pixel size.

[0101] Referring now to FIGS. **2**A-**3**C, various designs of a tunable spectral filter **120** are described, in accordance with one or more embodiments of the present disclosure. A tunable spectral filter **120** may generally have any component or combination of components suitable for passing a selected spectrum of light. Put another way, a tunable spectral filter **120** may generally have any component or combination of components suitable for limiting a spectrum of light.

[0102] In FIGS. **2**A-**3**C, the tunable spectral filter **120** accepts input light **202** and passes filtered light **204**, where a linewidth of the filtered light **204** is equal to or smaller than a linewidth of the input light **202**. As described previously herein, the tunable spectral filter **120** may operate on the illumination beam **104** or sample light **116**. In this way, the input light **202** may correspond to the illumination beam **104** or the sample light **116** depending on the location of the tunable spectral filter **120** within the inspection system **100**.

[0103] A tunable spectral filter **120** may operate in a transmission mode or a reflection mode to respectively transmit or reflect passed spectral components. For example, the filtered light **204** may correspond to light transmitted by one or more components of the tunable spectral filter **120** in a transmission mode. As another example, the filtered light **204** may correspond to light reflected by one or more components of the tunable spectral filter **120** in a reflection mode.

[0104] FIG. **2**A is a simplified schematic of a tunable spectral filter **120** formed as an etalon **206**, in accordance with one or more embodiments of the present disclosure. In embodiments, the tunable spectral filter **120** includes an etalon **206** to provide spectral filtering through optical resonance. For example, an etalon **206** may include two parallel reflective surfaces **208** forming an optical cavity, where the spectral width and transmissivity through the etalon **206** may be controlled by the reflectivity of the reflective surfaces **208**. The etalon **206** may be formed using any suitable technique. For example, the reflective surfaces **208** may be formed as two mirrors. As another example, the reflective surfaces **208** may be formed as faces of a solid material.

[0105] FIG. **2**B is a schematic diagram depicting spectral modes transmitted by an etalon **206**, in accordance with one or more embodiments of the present disclosure. For example, optical resonance within an etalon **206** may limit transmission to distinct frequencies separated by

$$\Delta v=c/2L \qquad (1)$$

(e.g., a free spectral range), where c is the speed of light and L is the separation distance between the reflective surfaces **208**. Further, the line width (LW) of transmitted light may be represented as δv. Analytically, an etalon **206** may be characterized by a finesse

$$F=\pi\sqrt{R}/1-R, \qquad (2)$$

which relates to a quality factor of the resonator. The spectral width may then be written as

$$\delta v=\Delta v/F. \qquad (3)$$

[0106] The transmissivity may be written as

$$T=1/1+F\sin^{2}\delta/2,\ \delta=4\pi/\lambda nL,\ F=4R/(1-R)^{2},\ F=\pi F/2, \qquad (4)$$

where n is a refractive index outside the reflective surfaces **208**.

[0107] Numerically, the spectral properties of a pulse propagating through an etalon **206** may be described as:

$$E_i(t,v)=e(t-t_0)^{2}/\tau^{2}e^{2\pi vt}, \qquad (5)$$

$$E_t(t,v)-(1-R)\sum_{n=1}^{\infty}R^{n-1}E_i(t-n\Delta t)e^{i(n-1)\delta\phi}, \qquad (6)$$

where

$$\Delta t=2L/c,\ \delta\phi=4\pi L/\lambda \qquad (7)$$

where E_i and E_t correspond to amplitudes of pulses of input light **202** and filtered light **204** (e.g., transmitted light), respectively.

[0108] FIGS. **2**C-**2**D depict spectral filtering properties of an etalon **206** under various conditions, in accordance with one or more embodiments of the present disclosure. FIG. **2**C is a plot of spectral transmission and reflection by an etalon **206** with length L of 0.1 mm and reflective surfaces **208** with a reflectivity R of 0.92, in accordance with one or more embodiments of the present disclosure. FIG. **2**D is a plot of spectral transmission and reflection by an etalon **206** with length L of 0.4 mm and reflective surfaces **208** with a reflectivity R of 0.91, in accordance with one or more embodiments of the present disclosure. In both FIGS. **2**C and **2**D, numerical values of the transmissivity and reflectivity of filtered light **204** are provided based on equations (5)-(7) (e.g., based on pulsed input light **202**) as well as analytical values of transmissivity of filtered light **204** are provided based on equations (1)-(4) (e.g., based on CW input light **202**). As depicted in FIGS. **2**C-**2**D, the use of pulsed input light **202** (e.g., from a mode-locked illumination source **102**) may result in lower peak transmission through an etalon **206** and greater spectral linewidth.
[0109] FIGS. **2**E-**2**F further depict how the structure of the etalon **206** impacts linewidth and transmissivity of an etalon **206**, in accordance with one or more embodiments of the present disclosure. FIG. **2**E is a surface plot of linewidth (LW) of an etalon **206** as a function of the reflectivity R of the reflective surfaces **208** as well as the separation L between the reflective surfaces **208**, in accordance with one or more embodiments of the present disclosure. FIG. **2**F is a plot of transmissivity of an etalon **206** as a function of the reflectivity R of the reflective surfaces **208** as well as the separation L between the reflective surfaces **208**, in accordance with one or more embodiments of the present disclosure. The data in FIGS. **2**E-**2**F is based on input light **202** having a 20 ps pulse with a 3 pm linewidth and a center wavelength of 193 nm. It is to be understood that this is merely illustrative and should not be interpreted as limiting the scope of the present disclosure.
[0110] FIGS. **3**A-**3**C depict variations of a tunable spectral filter **120** formed from at least one dispersive element **302** and a spatial filter **304**. Any type of dispersive element **302** or spatial filter **304** are within the spirit and scope of the present disclosure. For example, the dispersive element **302** may include a diffraction grating, a prism, or the like. As another example, the spatial filter **304** may include an aperture, beam block, or the like suitable for passing a selected portion of a spectrally-spread (e.g., spatially-dispersed) spectrum from the dispersive element **302**.
[0111] FIG. **3**A is a simplified schematic of a tunable spectral filter **120** including a dispersive element **302** formed as a prism, in accordance with one or more embodiments of the present disclosure. FIG. **3**B is a is a simplified schematic of a tunable spectral filter **120** including a dispersive element **302** formed as a diffraction grating, in accordance with one or more embodiments of the present disclosure. FIGS. **3**A and **3**B further depict a lens **306** suitable for focusing the spectrally-spread input light **202**.
[0112] In this configuration, the dispersive element **302** may spatially spread a spectrum of input light **202** and the spatial filter **304** may pass selected spectral components. The tunable spectral filter **120** may then recombine the passed spectral components with either by propagating back through the dispersive element **302** (e.g., if the spatial filter **304** reflects passed portions of the input light **202** as filtered light **204**) or through an additional dispersive element (e.g., if the spatial filter **304** transmits portions of the input light **202** as filtered light **204**).
[0113] It is contemplated herein that the type and configuration of a dispersive element **302** may impact various aspects of the tunable spectral filter **120** including, but not limited to, a sensitivity of spectral control, a transmissivity (e.g., efficiency), or a linewidth of filtered light **204**. As an illustration, the sensitivity of the tunable spectral filter **120** for providing spectral control may be characterized by a normalized wavelength separation metric $\delta d/d$, where δd is spatial separation of the spots focused by lens **306** at spatial filter **304** of a wavelength within the spectral linewidth, d is the spot size focused by lens **306** at spatial filter **304** of the center wavelength. This ratio metric of $\delta d/d$ defines the spectral filter performance.
[0114] For example, the normalized wavelength separation of a prism according to this metric may

be characterized as:

[00001] $\frac{d}{d} = \frac{D_0}{} .Math. \frac{1}{n} .Math. \frac{dn}{d}\delta\lambda\tan\ {}_0,\quad (6)$

where D.sub.0 is a diameter of the input light **202**, n is a refractive index of the prism, dn/dλ is a dispersion of the prism, λ is a central wavelength of the input light **202**, δλ is a linewidth of the input light **202**, and θ.sub.0 is an incidence angle of the input light **202**.

[0115] As another example, the normalized wavelength separation of a grating with a normal incidence angle of the input light **202** may be characterized by:

[00002] $\frac{d}{d} = \frac{1}{2.44}\sin\quad .Math. \frac{D_0}{} .Math. —,\quad (7)$

where θ is an exit angle of diffracted light from the grating. In the case of a Littrow configuration, the normalized wavelength separation may be characterized by:

[00003] $\frac{d}{d} = \frac{1}{1.22}\tan\quad .Math. \frac{D_0}{} .Math. —.\quad (7)$

[0116] FIG. **3**C is a plot depicting the normalized wavelength separation for a prism and a grating in a Littrow configuration, in accordance with one or more embodiments of the present disclosure. As shown in FIG. **3**C, the grating in the Littrow configuration may provide greater normalized wavelength separation than a prism for a given angle of incidence θ.

[0117] Referring now to FIGS. **2**A-**3**C, it is contemplated herein that different implementations of a tunable spectral filter **120** may provide different tradeoffs between parameters such as, but not limited to, size, transmissivity (e.g., efficiency), linewidth control, alignment tolerances, or manufacturability. For example, a tunable spectral filter **120** including an etalon **206** may provide a relatively compact solution, but may provide relatively low transmissivity, require sensitive alignment (and thus may be sensitive to vibrations or other mechanical movements), provide a relatively large linewidth, and/or require relatively large internal intensities between the reflective surfaces **208** (and thus may be power limiting). As another example, a tunable spectral filter **120** including a prism as a dispersive element **302** along with a spatial filter **304** may provide relatively high transmissivity and good alignment tolerances, but may be physically large, require correspondingly large beam sizes, and/or provide a relatively large linewidth. As another example, a tunable spectral filter **120** including a grating as a dispersive element **302** along with a spatial filter **304** may provide a relatively narrow linewidth and good alignment tolerances, but may provide relatively low efficiency and be challenging to manufacture for ultraviolet wavelengths.

[0118] It is further to be understood that FIGS. **2**A-**3**C are provided solely for illustrative purposes and should not be interpreted as limiting the scope of the disclosure. Rather, the tunable spectral filter **120** may include any component or combination of components suitable for controlling a spectrum of the illumination beam **104** and/or sample light **116**.

[0119] Referring again to FIG. **1**A, various additional aspects of the inspection system **100** are described in greater detail, in accordance with one or more embodiments of the present disclosure.

[0120] The one or more processors **124** of a controller **122** may include any processing element known in the art. In this sense, the one or more processors **124** may include any microprocessor-type device configured to execute algorithms and/or instructions. In embodiments, the one or more processors **124** may consist of a desktop computer, mainframe computer system, workstation, image computer, parallel processor, or any other computer system (e.g., networked computer) configured to execute a program configured to operate the inspection system **100**, as described throughout the present disclosure. It is further recognized that the term “processor” may be broadly defined to encompass any device having one or more processing elements, which execute program instructions from a non-transitory memory **126**. Further, the steps described throughout the present disclosure may be carried out by a single controller **122** or, alternatively, multiple controllers. Additionally, the controller **122** may include one or more controllers housed in a common housing or within multiple housings. In this way, any controller or combination of controllers may be separately packaged as a module suitable for integration into inspection system **100**.

[0121] The memory **126** may include any storage medium known in the art suitable for storing program instructions executable by the associated one or more processors **124**. For example, the memory **126** may include a non-transitory memory medium. By way of another example, the memory **126** 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 memory **126** may be housed in a common controller housing with the one or more processors **124**. In embodiments, the memory **126** may be located remotely with respect to the physical location of the one or more processors **124** and controller **122**. For instance, the one or more processors **124** of controller **122** may access a remote memory (e.g., server), accessible through a network (e.g., internet, intranet, and the like). Therefore, the above description should not be interpreted as a limitation on the present invention but merely an illustration.

[0122] The controller **122** may further be communicatively coupled with any of the components of the inspection system **100**. The controller **122** may thus receive data from any such components and/or may direct or otherwise control any such components via one or more control signals. In this way, the controller **122** (e.g., via the one or more processors **124**), may implement and/or direct the implementation of any process steps described herein.

[0123] FIG. **4** is a flow diagram illustrating steps performed in a method **400** for defect inspection, 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 inspection system **100** should be interpreted to extend to the method **400**. It is further noted, however, that the method **400** is not limited to the architecture of the inspection system **100**.

[0124] FIG. **4** is a flowchart of an example inspection method, in accordance with one or more embodiments of the present disclosure.

[0125] In embodiments, the method **400** includes a step **402** of generating an illumination beam **104**. The illumination beam **104** may have multiple longitudinal modes such that the linewidth used for imaging may be adjusted. For example, the illumination beam **104** may be a pulsed beam (e.g., from a mode-locked laser source or any other suitable source) or a CW beam having multiple longitudinal modes.

[0126] In embodiments, the method **400** includes a step **404** of directing the illumination beam **104** to a sample **110**. The step **404** may include directing the illumination beam **104** to the sample **110** at any suitable angle.

[0127] In embodiments, the method **400** includes a step **406** of selecting a measurement mode from at least a first measurement mode or a second measurement mode for imaging the sample **110** with an inspection system **100**. For example, the first measurement mode may provide a relatively larger linewidth for at least the illumination beam **104** or sample light **116** collected from the sample **110**, which may result in higher chromatic aberration by the objective lens in the first measurement mode relative to the second measurement mode. Further, the image pixel size may be larger for the first measurement mode than for the second measurement mode. In this way, the first measurement mode may be suitable for, but is not limited to, applications where surface haze from the sample **110** is relatively low and/or suppressed by the imaging sub-system **112**. In some applications, the first measurement mode is used when sensor noise (e.g., noise from a detector **118**) is the dominant noise source. In this case, the SNR of defects on the sample **110** may be increased by increasing the image pixel size. Further, the larger image pixel size may tolerate more chromatic aberration associated with the relatively larger linewidth. The second measurement mode may be suitable for, but not limited to, applications where surface haze from the sample **110** is relatively high and in some cases is the dominant noise source. In this case, the SNR of defects may be increased by decreasing the image pixel size. Further, the linewidth may be reduced to provide a diffraction-limited PSF or at least a PSF smaller than the image pixel size.

[0128] However, it is to be understood that the description of the first and second measurement

modes is merely illustrative and should not be interpreted as limiting the scope of the present disclosure. For example, the step **406** may include selecting an additional measurement mode in some applications. In a general sense, an inspection system **100** may be configurable to operate in any number of measurement modes. As an illustration, the spectral linewidth used to generate an image (e.g., a linewidth associated with the illumination beam **104** and/or the sample light **116** passed to a detector **118**) and/or the image pixel size may be adjusted to any values in any number of measurement modes. As an illustration, the spectral linewidth and/or the image pixel size may be adjusted to maximize a SNR of defects within a tolerance based on any imaging conditions.
[0129] The spectral linewidth used to generate an image of the illumination beam **104** and/or the sample light **116** (e.g., a spectral linewidth) may be adjusted using any technique known in the art. For example, the spectral linewidth may be adjusted using a tunable spectral filter **120**. Further, the spectral linewidth may be adjusted by controlling a linewidth of the illumination beam **104** prior to the sample **110** or by controlling a linewidth of the sample light **116** passed to a detector **118**.
[0130] The image pixel size may be adjusted using any technique known in the art. For example, the image pixel size may be adjusted by controlling a magnification (e.g., an optical magnification) of the imaging sub-system **112** used to generate an image of the sample **110**. As another example, the image pixel size may be adjusted by selecting a detector **118** from multiple available detectors **118** having different sensor pixel sizes.
[0131] In embodiments, the method **400** includes a step **408** of generating one or more images of the sample using the selected measurement mode. In embodiments, the method **400** includes a step **410** of at least one of identifying or characterizing one or more defects on the sample based on the one or more images.
[0132] 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 interactable and/or physically interacting components and/or wirelessly interactable and/or wirelessly interacting components and/or logically interactable and/or logically interacting components.
[0133] 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

1. An inspection system comprising: an illumination source configured to generate an illumination beam; an illumination sub-system including one or more illumination optics configured to direct the illumination beam to a sample; an imaging sub-system comprising: an objective lens configured to collect sample light from the sample in response to the illumination beam, wherein the objective lens exhibits chromatic aberration within a spectrum of the illumination beam; and one or more

detectors to image the sample based on at least a portion of the sample light collected by the objective lens, wherein an image pixel size is adjustable, wherein the image pixel size is a size of pixels of the one or more detectors projected to a plane of the sample; and a tunable spectral filter with an adjustable linewidth configured to selectively adjust a spectrum of at least one of the illumination beam or the sample light, wherein the imaging sub-system and the tunable spectral filter are configurable according to at least a first measurement mode and a second measurement mode, wherein the first measurement mode provides a relatively larger linewidth and a relatively larger image pixel size than the second measurement mode.
2. The inspection system of claim 1, wherein the image pixel size is adjustable by controlling a magnification of the imaging sub-system.
3. The inspection system of claim 1, wherein the first measurement mode provides a relatively higher chromatic aberration by the objective lens than the second measurement mode.
4. The inspection system of claim 1, further comprising a controller communicatively coupled to at least one of the tunable spectral filter or the imaging sub-system, wherein the controller includes one or more processors configured to execute program instructions causing the one or more processors to: receive one or more images of the sample from the one or more detectors; and at least one of identify or characterize one or more defects on the sample based on the one or more images.
5. The inspection system of claim 1, wherein the illumination source comprises a pulsed laser.
6. The inspection system of claim 5, wherein the illumination beam includes pulses with temporal pulse widths greater than approximately 1 picometer.
7. The inspection system of claim 5, wherein the illumination beam includes pulses with temporal pulse widths greater than approximately 10 picometers.
8. The inspection system of claim 1, wherein the tunable spectral filter adjusts the spectrum of the illumination beam.
9. The inspection system of claim 8, wherein the tunable spectral filter is located within the illumination source.
10. The inspection system of claim 8, wherein the tunable spectral filter is located between the illumination source and the sample.
11. The inspection system of claim 1, wherein the tunable spectral filter adjusts the spectrum of the sample light.
12. The inspection system of claim 1, wherein the spectrum of the illumination beam includes wavelengths in an ultraviolet spectral (UV) range or lower.
13. The inspection system of claim 1, wherein the tunable spectral filter comprises: an etalon.
14. The inspection system of claim 1, wherein the tunable spectral filter comprises: one or more prisms; and a spatial filter.
15. The inspection system of claim 1, wherein the tunable spectral filter comprises: one or more diffraction gratings; and a spatial filter.
16. The inspection system of claim 1, further comprising: a haze mask when operating in at least the first measurement mode, wherein the haze mask is configured to pass light scattered from one or more particles on the sample and suppress scattered light from a surface of the sample.
17. The inspection system of claim 16, wherein the haze mask comprises: a waveplate; and a polarizer.
18. An inspection method comprising: generating an illumination beam; directing the illumination beam to a sample; selecting a measurement mode from at least a first measurement mode or a second measurement mode for imaging the sample with an inspection system, wherein the inspection system includes an imaging sub-system comprising: an objective lens configured to collect sample light from the sample in response to the illumination beam, wherein the objective lens exhibits chromatic aberration within a spectrum of the illumination beam; and one or more detectors to image the sample based on at least a portion of the sample light collected by the

objective lens, wherein an image pixel size is adjustable, wherein the image pixel size is a size of pixels of the one or more detectors projected to a plane of the sample, wherein the inspection system further includes a tunable spectral filter with an adjustable linewidth configured to selectively adjust a spectrum of at least one of the illumination beam or the sample light, wherein the first measurement mode provides a relatively larger linewidth and a relatively larger image pixel size than the second measurement mode; generating one or more images of the sample using the measurement mode selected from at least the first measurement mode or the second measurement mode; and at least one of identifying or characterizing one or more defects on the sample based on the one or more images.

19. An inspection system comprising: a controller communicatively coupled to at least one of an illumination source configured to generate an illumination beam, an illumination sub-system including one or more lenses configured to direct the illumination beam to a sample, an imaging sub-system, or a tunable spectral filter, wherein the imaging sub-system comprises: an objective lens configured to collect sample light from the sample in response to the illumination beam, wherein the objective lens exhibits chromatic aberration within a spectrum of the illumination beam; and one or more detectors to image the sample based on at least a portion of the sample light collected by the objective lens, wherein an image pixel size is adjustable, wherein the image pixel size is a size of pixels of the one or more detectors projected to a plane of the sample; wherein the tunable spectral filter provides an adjustable linewidth configured to selectively adjust a spectrum of at least one of the illumination beam or the sample light, wherein the imaging sub-system and the tunable spectral filter are configurable according to at least a first measurement mode and a second measurement mode, wherein the first measurement mode provides a relatively larger linewidth and a relatively larger image pixel size than the second measurement mode; and wherein the controller includes one or more processors configured to execute program instructions causing the one or more processors to: receive one or more images of the sample from at least one of the one or more detectors; and at least one of identify or characterize one or more defects on the sample based on the one or more images.

20. The inspection system of claim 19, wherein the program instructions are further configured to cause the one or more processors to: control at least one of the tunable spectral filter or the imaging sub-system to generate each of the one or more images in a selected measurement mode selected from one or more measurement modes including the first measurement mode and the second measurement mode.

21. The inspection system of claim 19, wherein the image pixel size is adjustable by controlling a magnification of the imaging sub-system.

22. The inspection system of claim 19, wherein the first measurement mode provides a relatively higher chromatic aberration by the objective lens than the second measurement mode.

23. The inspection system of claim 19, wherein the tunable spectral filter adjusts the spectrum of the illumination beam.

24. The inspection system of claim 19, wherein the tunable spectral filter adjusts the spectrum of the sample light.

25. The inspection system of claim 19, wherein the spectrum of the illumination beam includes wavelengths in an ultraviolet spectral (UV) range or lower.