

APPARATUS FOR SURFACE PROFILE MEASUREMENT

Technical Field

5

The present disclosure generally relates to surface profile measurement. More particularly, the present disclosure describes various embodiments of an apparatus for measuring the surface profile of an object.

10 Background

Surface profile of objects is an important property for quality inspection of the objects in many industries. Particularly, in the semiconductor industry, the surface profile of semiconductor devices such as wafers or substrates need to be measured and
15 inspected as part of quality control and assurance processes. One conventional way of measuring the surface profile of an object is by using confocal microscopy techniques. Specifically, confocal sensors are used to measure arbitrary points on the surface of the object to determine their relative heights on the surface. These point-by-point measurements are subsequently combined to estimate the surface
20 profile of the object. However, measuring of the surface profile is slow because of the time taken for point-by-point measurements of individual points on the surface. The arbitrary points also do not cover all areas of the surface, potentially excluding relevant regions of interest of the surface profile.

25 Therefore, in order to address or alleviate at least one of the aforementioned problems and/or disadvantages, there is a need to provide an improved apparatus for measuring the surface profile of an object.

Summary

30

According to an aspect of the present disclosure, there is an apparatus for measuring a surface profile of an object, the apparatus comprising:

a light source assembly comprising a broadband light source;

a confocal microscopy assembly comprising:

5 a beam splitter for directing uniform light from the broadband light source to the object;

a pinhole device comprising an array of pinholes, the pinhole device configured for passing the uniform light from the beam splitter through the pinholes to the object;

10 a set of incident optical elements for directing the uniform light from the pinhole device to the object and causing chromatic aberration of the uniform light passing through the incident optical elements; and

the pinhole device configured for passing light reflected from the object through the pinholes to the beam splitter, the reflected light comprising spectral information of the surface profile based on the chromatic aberration; and

15 an optical detection assembly comprising:

an optical detector for receiving the reflected light from the beam splitter;

and

20 a set of detection optical elements for directing the reflected light from the beam splitter to the optical detector,

wherein the surface profile of the object is measurable based on spectral information of the reflected light received by the optical detector, the spectral information representing heights across the surface profile.

25 An apparatus for measuring a surface profile of an object according to the present disclosure are thus disclosed herein. Various features, aspects, and advantages of the present disclosure will become more apparent from the following detailed description of the embodiments of the present disclosure, by way of non-limiting examples only, along with the accompanying drawings.

30

Brief Description of the Drawings

Figure 1 is an illustration of an apparatus for measuring the surface profile of the object, the apparatus having a colour camera, according to some embodiments of the present disclosure.

Figure 2 is a flowchart illustration of a method for measuring the surface profile of the object, according to some embodiments of the present disclosure.

Figures 3 to 5 are illustrations of a pinhole device of the apparatus, according to some embodiments of the present disclosure.

Figure 6 is an illustration of a light source of the apparatus, according to some embodiments of the present disclosure.

Figure 7 is an illustration of a spectral image of the object captured by the apparatus, according to some embodiments of the present disclosure.

Figure 8 is an illustration of the apparatus in another configuration, according to some embodiments of the present disclosure.

Figure 9 is an illustration of another apparatus having a hyperspectral imaging assembly, according to some embodiments of the present disclosure.

Figure 10 is an illustration of a hyperspectral image of the object captured by the apparatus, according to some embodiments of the present disclosure.

Figure 11 is an illustration of another apparatus having the hyperspectral imaging assembly and configured for line scanning, according to some embodiments of the present disclosure.

Figure 12 is an illustration of the hyperspectral image of the object captured by the apparatus using line scanning, according to some embodiments of the present disclosure.

5

Figure 13 is an illustration of another apparatus having the hyperspectral imaging assembly and a Nipkow disk, according to some embodiments of the present disclosure.

10 Figures 14 and 15 are illustrations of the Nipkow disk, according to some embodiments of the present disclosure.

Figure 16 is an illustration of another apparatus having the colour camera and Nipkow disk, according to some embodiments of the present disclosure.

15

Detailed Description

For purposes of brevity and clarity, descriptions of embodiments of the present disclosure are directed to an apparatus for measuring a surface profile of an object, in accordance with the drawings. While aspects of the present disclosure will be described in conjunction with the embodiments provided herein, it will be understood that they are not intended to limit the present disclosure to these embodiments. On the contrary, the present disclosure is intended to cover alternatives, modifications and equivalents to the embodiments described herein, which are included within the scope of the present disclosure as defined by the appended claims. Furthermore, in the following detailed description, specific details are set forth in order to provide a thorough understanding of the present disclosure. However, it will be recognized by an individual having ordinary skill in the art, i.e. a skilled person, that the present disclosure may be practiced without specific details, and/or with multiple details arising from combinations of aspects of particular embodiments. In a number of

20

25

30

instances, well-known systems, methods, procedures, and components have not been described in detail so as to not unnecessarily obscure aspects of the embodiments of the present disclosure.

- 5 In embodiments of the present disclosure, depiction of a given element or consideration or use of a particular element number in a particular figure or a reference thereto in corresponding descriptive material can encompass the same, an equivalent, or an analogous element or element number identified in another figure or descriptive material associated therewith.

10

- References to “an embodiment / example”, “another embodiment / example”, “some embodiments / examples”, “some other embodiments / examples”, and so on, indicate that the embodiment(s) / example(s) so described may include a particular feature, structure, characteristic, property, element, or limitation, but that not every
15 embodiment / example necessarily includes that particular feature, structure, characteristic, property, element or limitation. Furthermore, repeated use of the phrase “in an embodiment / example” or “in another embodiment / example” does not necessarily refer to the same embodiment / example.

- 20 The terms “comprising”, “including”, “having”, and the like do not exclude the presence of other features / elements / steps than those listed in an embodiment. Recitation of certain features / elements / steps in mutually different embodiments does not indicate that a combination of these features / elements / steps cannot be used in an embodiment.

25

- As used herein, the terms “a” and “an” are defined as one or more than one. The use of “/” in a figure or associated text is understood to mean “and/or” unless otherwise indicated. The term “set” is defined as a non-empty finite organization of elements that mathematically exhibits a cardinality of at least one (e.g. a set as defined herein can
30 correspond to a unit, singlet, or single-element set, or a multiple-element set), in

accordance with known mathematical definitions. The recitation of a particular numerical value or value range herein is understood to include or be a recitation of an approximate numerical value or value range. The terms “first”, “second”, etc. are used merely as labels or identifiers and are not intended to impose numerical requirements
5 on their associated terms.

In representative or exemplary embodiments of the present disclosure, with reference to Figure 1, there is an apparatus 20 for measuring a surface profile of an object 30. The apparatus 20 includes a light source assembly 100, a confocal microscopy
10 assembly 200, and an optical detection assembly 300. The apparatus 20 further includes a table for supporting the object 30 during the measurement. The table may be configured to be displaceable, such as to shift the object 30 to measure different areas of, or the whole of, the surface profile.

15 The light source assembly 100 includes a broadband light source 110 configured for emitting broadband uniform light that spans across a broad continuous range of wavelengths. For example, the broadband uniform light is white light that includes wavelengths that span across the visible colour spectrum and may include wavelengths in the infrared and/or ultraviolet spectra.

20

The confocal microscopy assembly 200 includes a beam splitter 210 configured for directing uniform light from the broadband light source 110 to the object 30. The beam splitter 210 is disposed between the broadband light source 110 and the object 30. The confocal microscopy assembly 200 includes a pinhole device 220 having an array
25 of pinholes 222, the pinhole device 220 configured for passing the uniform light from the beam splitter 210 through the pinholes 222 to the object 30. More specifically, the pinholes 222 are arranged to block out most of the light from the beam splitter 210 and to allow only some of the light to pass through to the object 30, each pinhole 222 acting as a point illumination source of a confocal microscope. The pinholes 222 may
30 be equal-distanced and circular or squarish.

The confocal microscopy assembly 200 includes a set of incident optical elements 230, such as lenses and/or mirrors, for directing the uniform light from the pinhole device 220 to the object 30 and causing chromatic aberration of the uniform light passing through the incident optical elements 230. Additionally, the pinhole device 220 is configured for passing light reflected from the object 30 through the pinholes 222 to the beam splitter 210, the reflected light including spectral information of the surface profile based on the chromatic aberration. More specifically, the pinholes 222 are arranged to allow only light that is focused on and reflected from the object 30 to pass through to the beam splitter 210. The pinhole device 220 blocks all reflected light that is not focused on the object 30 as such reflected light would not be incident on the pinholes 222.

The optical detection assembly 300 includes an optical detector 310 for receiving the reflected light from the beam splitter 220. The optical detection assembly 300 includes a set of detection optical elements 320 for directing the reflected light from the beam splitter 210 to the optical detector 310. The surface profile of the object 30 is measurable based on spectral information of the reflected light received by the optical detector 310, the spectral information representing heights across the surface profile. For example, the spectral information includes information about the wavelengths of the reflected light that is focused on the object 30 and reflected to the pinholes 222, wherein the wavelengths can be used to determine the height variation across the surface profile.

In various embodiments of the present disclosure, with reference to Figure 2, there is a method 400 for measuring the surface profile of the object 30, wherein the method 400 is performed using the apparatus 20. The method includes a step 402 of directing uniform light from the broadband light source 110 to the object 30 using the beam splitter 210. The method includes a step 404 of passing the uniform light from the beam splitter 210 through the array of pinholes 222 of the pinhole device 220 to the

object 30. The method includes a step 406 of directing the uniform light from the pinhole device 220 to the object 30 using the set of incident optical elements 230, the incident optical elements 230 causing chromatic aberration of the uniform light passing through the incident optical elements 230. The method includes a step 408 of
5 passing light reflected from the object 30 through the array of pinholes 222 to the beam splitter 210, the reflected light including spectral information of the surface profile based on the chromatic aberration. The method includes a step 410 of directing the reflected light from the beam splitter 210 to the optical detector 310 using the set of detection optical elements 320. The method includes a step 412 of receiving, by the
10 optical detector 310, the reflected light from the beam splitter 210. The method includes a step 414 of measuring the surface profile of the object 30 based on spectral information in the reflected light received by the optical detector 310, the spectral information representing heights across the surface profile.

15 As described above, the incident optical elements 230 cause chromatic aberration of the uniform light propagating from the pinhole device 220 to the object 30, and the reflected light from the object 30 includes spectral information based on the chromatic aberration, such as wavelengths. More specifically, the incident optical elements 230 cause axial or longitudinal chromatic aberration to the light, resulting in different
20 wavelengths of the light focusing along different focal distances from the incident optical elements 230 to the object 30. Due to the chromatic aberration, the different wavelengths of the light focuses on different heights or depths across the surface profile of the object 30 relative to a reference plane along the surface profile. For example, red light (having wavelengths such as around 620 to 720 nm) focuses on a
25 lower height, blue light (having wavelengths such as around 460 to 500 nm) focuses on a higher height, and green light (having wavelengths such as around 500 to 570 nm) focuses on a middle height in between, wherein the heights are relative to the reference plane.

The wavelengths that are clearly focused on the surface profile of the object 30 reflect from the object 30 to the pinhole device 220, the reflected light reversely following the same propagation paths as the incident light arriving and focused on the surface profile. These wavelengths of the reflected light that are focused on the object 30 are passed through the pinhole device 220 to the beam splitter 210. Other wavelengths of the reflected light that are not focused on the object 30 may be reflected back but they are not aligned with the pinholes 222 and cannot pass through the pinholes 222. In other words, the pinhole device 220 blocks out all reflected light that is not focused on the object 30. Hence, only certain wavelengths of the reflected light are reflected from the object 30 through the pinholes 222 to the beam splitter 210. The reflected light is subsequently imaged on a conjugate plane of the pinhole device 210 and received by the optical detector 310. As only the wavelengths of the reflected light that are focused on different heights across the surface profile are reflected from the object 30 and received by the optical detector 310, these wavelengths are representative of the heights and the surface profile can be measured in three dimensions based on these wavelengths. A colour spectral image of the surface profile can hence accurately measure the three-dimensional height contours across the surface profile without vertical scanning or movement of any component of the apparatus 20.

As the pinhole device 220 blocks out most of the light that is incident on the surfaces of the pinhole device 220, i.e. on areas around the pinholes 222, the pinhole device 220 may include suitable optical elements to minimize or prevent reflection of light. For example, light incident on the top surface of the pinhole device 220 may reflect back to the beam splitter 210 and merge with the reflected light from the object 30, potentially affecting accuracy of the surface profile measurement. These optical elements may also improve focusing of light into the pinholes 222 which would in turn improve the spectral imaging and measurement of the surface profile.

As shown in Figure 3, the pinhole device 220 may include one or more arrays of microlenses 224 arranged with the array of pinholes 222. For example, the pinhole

device 220 includes a first array of microlenses 224 arranged on top of the pinholes 222, such that each pinhole 222 is associated with a microlens 224 of the first array configured for focusing light from the beam splitter 220 into the respective pinhole 222. The pinhole device 220 may optionally include a second array of microlenses 224
5 arranged below the pinholes 222, such that each pinhole 222 is associated with a microlens 224 of the second array configured for focusing light reflected from the object 30 into the respective pinhole 222. The pinholes 222 and microlenses 224 arrays may be formed separately and coupled together, or they may be integrated together as a single unit.

10

Each pinhole 222 is paired with at least one microlens 224 and they cooperate to focus light into the centre of the respective pinhole 222. The microlenses 224 are specifically arranged with the pinholes 222 such that their centre focal points are aligned to focus light incident on the microlenses 224 into the pinholes 222. This
15 collects more light energy on one or both sides of the pinhole device 220 and increases the amount of light directed into each pinhole 222, thereby improving the light efficiency because light efficiency is very low for conventional confocal microscopes. The curved surfaces of the microlenses 224 can expel and remove unwanted light incident on them, thereby improving the quality of light passing through
20 the pinholes 222.

As shown in Figure 3, the microlenses 224 are packed together such that they are in physical contact with each other or with some gap in between. As the diameter of the pinholes 222 is smaller than the diameter of the microlenses 224, there are gaps
25 between the pinholes 222. As shown in Figure 4, these gaps are represented as pitches P1 and P2 with respect to two perpendicular directions, i.e. along the X-axis and Y-axis, respectively. By projecting the pinholes 222 to the object 30, the pinholes 222 correspond to multiple individual points on the surface profile of the object 30, and the gaps or pitches P1 and P2 between the pinholes 222 correspond to gaps between
30 the multiple points.

An advantage of the pinholes 222 is that the multiple points on the surface profile can be simultaneously measured for their heights. The multiple points are distributed across at least a sample area, or in some cases substantially the whole, of the surface profile, enabling the apparatus 20 to perform quick sampling measurement of the sample area. Notably, the number of points is dependent on the number of pinholes 222, so a larger number of pinholes 222 can increase the sample area being measured and/or increase the measurement resolution. The high-speed sampling measurement of multiple points of the sample area can be useful for various practical applications, especially when quick inspection of a batch of objects 30 is required.

As the pinhole device 220 remains stationary during this sampling measurement, the gaps between the multiple points are not imaged and measured. To address this, in some embodiments, the confocal microscopy assembly 200 may include an actuation mechanism 240 for planarly moving the pinhole device 220. As shown in Figure 5, the actuation mechanism 240 may be configured to planarly move the pinhole device 220 along the X-axis and/or Y-axis. Alternatively or additionally, the actuation mechanism 240 may be configured to planarly rotate the pinhole device 220 around the Z-axis such that the pinhole device 220 remains on the XY-plane during the rotations. For example, the actuation mechanism 240 includes actuators such as motors and piezoelectric actuators.

When the pinhole device 220 moves planarly along the XY-plane, the pinholes 222 and corresponding points on the surface profile are moved across the surface profile, enabling the light to reach and scan a continuous surface area and substantially the whole of the surface profile. Substantially all areas of the surface profile can be scanned and measured without any gaps (or at least minimized), thereby mitigating risk of excluding relevant regions of interest of the surface profile. A more detailed measurement of the surface profile can hence be obtained, allowing for higher quality inspection of the object 30.

In one embodiment as shown in Figure 1, the apparatus 20 includes the light source assembly 100, confocal microscopy assembly 200, and optical detection assembly 300 as described above. The light source assembly 100 includes the broadband light source 110 is configured for emitting broadband uniform light such as white light. As shown in Figure 6, the broadband light source 110 includes a set of light lamps 112. The light lamps 112 may be incandescent lamps or broadband white light emitting diodes (LEDs). For example, the incandescent lamps are halogen lamps such as tungsten halogen lamps. The light lamps 112 may be of low power, such as 50 W, to reduce waste heat generated from use of the apparatus 20. Low-powered light lamps 112 would obviate the need for cooling devices such as fans, which would in turn reduce mechanical vibrations and power consumption. Nevertheless, the light source assembly 100 may include a small heat sink to remove any heat generated from the broadband light source 110.

15

The broadband light source 110 includes an optical aperture 114 for directing the uniform light emitted from the light lamps 112 out of the broadband light source 110. The optical aperture 114 may be circular and is configured to control the diameter of the light beam emitted out of the broadband light source 110 to the confocal microscopy assembly 200. The broadband light source 110 may include an optical integrating sphere 116 configured to integrate the light energy from the light lamps 112. The optical integrating sphere 116, also known as an Ulbricht sphere, is an optical component having a hollow spherical cavity with an internal reflective coating for uniform scattering of light and to reduce loss of light. As shown in Figure 6, the light lamps 112 are arranged around the optical integrating sphere 116 such that light from the light lamps 112 is directed into the cavity towards the internal reflective coating of the optical integrating sphere 116, so that the internal reflective coating reflects the light to the optical aperture 114.

25

The broadband light source 110 may include an optical bandpass filter configured for filtering out light outside of a predefined wavelength range. The optical bandpass filter is disposed between the light lamps 112 and the optical integrating sphere 116, such as at the optical aperture 114. For example, the optical bandpass filter includes a dichroic filter or dielectric mirror. The predefined wavelength range may correspond to the visible colour spectrum, or a region thereof such as from red to blue, and the optical bandpass filter allows all visible light to pass through and exit the optical aperture 114. Undesired light outside of the visible colour spectrum, such as infrared and ultraviolet light, are blocked out by the optical bandpass filter. Notably, infrared light is hotter than visible light and by blocking out infrared light, less heat is transmitted out of the optical aperture 114, thereby mitigating risk of heat damage to the confocal microscopy assembly 200.

The uniform light from the broadband light source 110 may propagate through the optical aperture 114 directly to the confocal microscopy assembly 200. Alternatively, the light source assembly 100 may include a Köhler illumination device 120 having one or more lenses disposed between the broadband light source 110 and the confocal microscopy assembly 200. The Köhler illumination device 120 provides parallel and uniform light to the confocal microscopy assembly 200.

The confocal microscopy assembly 200 includes the beam splitter 210, pinhole device 220, and set of incident optical elements 230 as described above. The incident optical elements 230 include an objective lens 232 for focusing light on the object 30 and a tube lens 234 for focusing the reflected light from the object 30 on the pinhole device 220. The incident optical elements 230 further include a chromatic aberration lens 236 disposed between the objective lens 232 and tube lens 234 for causing the chromatic aberration of the light. The chromatic aberration lens 236 is designed with specific chromatic aberration properties and good linearity. Different chromatic aberration lens 236 may be used depending on the desired measurement range and resolution. Alternatively, the chromatic aberration lens 236 may be integrated with the objective

lens 232 as a single lens element. With chromatic aberration, the different wavelengths of the light are more clearly separated, and the different heights of the surface profile can be more clearly distinguished, so that the surface profile can be imaged and measured in 3D.

5

The optical detection assembly 300 includes the optical detector 310 and set of detection optical elements 320 as described above. The detection optical elements 320 may include an imaging lens 322 for directing the reflected light from the beam splitter 210 to the optical detector 310. The optical detector 310 may include a colour camera 312 having image sensors for the red-green-blue (RGB) colours, such as
10 CCD or CMOS image sensors. The imaging lens 322 is configured for focusing the reflected light containing the spectral information on the image sensors of the colour camera 312, thereby imaging on the colour camera 312 the spectral information in the reflected light from the surface profile of the object 30.

15

The working spectrum range of the colour camera 312 may span across the visible colour spectrum and optionally to the infrared and/or ultraviolet spectra. For example, the working wavelength range of the colour camera 312 may be around 380 to 1000 nm. An infrared filter of the colour camera 312 may be added to exclude the infrared /
20 near-infrared spectra. As described above, different heights or depths across the surface profile are imaged as different colours according to the precise spectral information and wavelengths of the reflected light, and the captured spectral image of the surface profile can accurately measure the three-dimensional surface profile, wherein different heights across the surface profile are represented as different
25 spectral colours in the spectral image. Figure 7 shows an example of an RGB spectral image 40 including the calibrated RGB curves of the object 30 captured by the colour camera 312. The apparatus 20 can be integrated or coupled with an image processing module to generate the surface topography of the object 30 based on the spectral image 40. More specifically, the image processing module calculates the
30 surface profile of the object 30 based on spectral image 40 received by the optical

detector 310, wherein the colours or wavelengths of each point (corresponding to the pinholes 222) represent the height of that point on the surface profile. All the points collectively represent the height variation across the whole surface profile.

5 In one embodiment, the light source assembly 100, confocal microscopy assembly 200, and optical detection assembly 300 are arranged as shown in Figure 1. When the apparatus 20 is in use, uniform light from the light source assembly 100 passes through the beam splitter 210 to the object 30, reflects from the object 30 back to the beam splitter 210, and the beam splitter 210 reflects the light to the optical detection
10 assembly 300. As the beam splitter 210 is configured for both transmission and reflection (preferably in equal ratios), there may be other configurations of the apparatus 20. In one embodiment as shown in Figure 8, when the apparatus 20 is in use, light from the light source assembly 100 reaches the beam splitter 210, reflects to the object 30, reflects from the object 30 back to the beam splitter 210, and passes
15 through the beam splitter 210 to the optical detection assembly 300.

In summary, in the embodiments as shown in Figures 1 and 8, the apparatus 20 includes the light source assembly 100, confocal microscopy assembly 200, and optical detection assembly 300 configured for measuring the surface profile of the
20 object 30. The light source assembly 100 includes the broadband light source 110 and the Köhler illumination device 120. The confocal microscopy assembly 200 includes the beam splitter 210 and the pinhole device 220 having the array of pinholes 222 and one or more arrays of microlenses 224 arranged with the array of pinholes 222. The confocal microscopy assembly 200 further includes the set of incident optical
25 elements 230 and the actuation mechanism 240 for planarly moving the pinhole device 220 along the X-axis and Y-axis. The incident optical elements 230 include the objective lens 232, tube lens 234, and chromatic aberration lens 236. The optical detection assembly 300 includes the optical detector 310 having the colour camera 312, and further includes the set of detection optical elements 320 having the imaging
30 lens 322 for focusing the reflected light on the colour camera 312.

In one embodiment as shown in Figure 9, the apparatus 20 is substantially similar to the embodiment as shown in Figure 1 except for the optical detection assembly 300. It will be appreciated that various aspects described above for the embodiment of Figure 1 will apply similarly or analogously to the embodiment of Figure 9, and vice versa. The optical detector 310 includes a hyperspectral camera 314 and the optical detection assembly 300 may be referred to as a one-shot hyperspectral imaging assembly 302. The hyperspectral camera 314 may capture the spectral information in the reflected light more precisely and obtain the hyperspectral information of the surface profile. Further, the hyperspectral camera 314 is a one shot or single shot hyperspectral camera that captures only one image to obtain the hyperspectral information of the surface profile. The hyperspectral camera 314 can capture the hyperspectral information in full colour or in monochrome. For example, the hyperspectral camera 314 is a high-resolution full colour or monochrome camera.

15

Normal spectral imaging or multispectral imaging captures and processes images usually in three broad bands of wavelengths corresponding to the RGB colours because the human eye sees colours of visible light in mostly these three bands. Hyperspectral imaging can capture and process images across the electromagnetic spectrum ranging from infrared to ultraviolet spectra or even including the X-ray spectrum. Hyperspectral imaging divides the electromagnetic spectrum into many more bands compared to the usual three RGB bands and covering a wide range of wavelengths with fine wavelength resolution. Hyperspectral imaging measures a multitude of continuous spectral bands, as opposed to normal spectral imaging which measures spaced broad RGB spectral bands. The hyperspectral camera 314 can capture and process images of the object 30 at a very large number of fine wavelengths and the hyperspectral information can be broken down into a very large number of colours corresponding to the fine wavelengths.

25

The one-shot hyperspectral imaging assembly 302 includes an aperture device 330 for passing through the reflected light from beam splitter 210 to the hyperspectral camera 314. The aperture device 330 includes at least one aperture or hole for the light to pass through. The one-shot hyperspectral imaging assembly 302 includes a
5 wavelength differentiation device 340 disposed between the aperture device 330 and the hyperspectral camera 314 for differentiating the reflected light to more clearly distinguish the reflected light by the spectral information i.e. the wavelengths. The wavelength differentiation device 340 may be either an optical grating for diffracting the reflected light or an optical prism for dispersing the reflected light.

10

In the one-shot hyperspectral imaging assembly 302 as shown in Figure 9, the set of detection optical elements 320 includes the imaging lens 322 disposed in front of the hyperspectral camera 314 and behind the optical grating 340. The imaging lens 322 is configured for focusing the reflected light from the optical grating 340 on the image
15 sensors of the hyperspectral camera 314, thereby imaging on the hyperspectral camera 314 the spectral information in the reflected light from the surface profile of the object 30. The detection optical elements 320 further include a collimator 324 disposed between the aperture device 330 and the optical grating 340. The collimator 324 is a device, such as a curved lens or mirror, that narrows a light beam and align it
20 to a specific direction. Notably, the collimator 324 collimates the reflected light from the aperture device 330 to the optical grating 340 which more clearly distinguishes the light into its continuous spectrum of wavelengths. The detection optical elements 320 may further include a relay lens 326 disposed between the beam splitter 210 and the aperture device 330. The relay lens 326 is configured for projecting, on the aperture
25 device 330 via the beam splitter 210, the image of the surface profile formed on the pinhole device 220.

The imaging lens 322 projects the refracted wavelengths of the reflected light on the hyperspectral camera 314 as discrete wavelengths according to the spectral
30 information in the reflected light. Due to effects of the microlenses 224 which increase

the amount of light directed into the pinholes 222, the image sensitivity is increased and the full spectrum of each point on the surface profile of the object 30 is imaged by the hyperspectral camera 314. Figure 10 shows an example of a hyperspectral image 50 of the object 30 captured using the one-shot hyperspectral imaging assembly 302.

5 The apparatus 20 can be integrated or coupled with an image processing module to generate the surface topography of the object 30 based on the hyperspectral image 50. In addition to the surface topography, the subsurface topography and multi-layer thicknesses on the surface of the object 30 can be precisely measured and inspected because of the full hyperspectral spectrum of the 3D surface profile. Hyperspectral
10 imaging can hence measure the full spectrum of the surface profile in high resolution and detail, and the apparatus 20 has broad applications in various fields such as but not limited to online inspection and measurements for semiconductor, electronics, precision engineering, optics, biomedical agriculture, and food industries.

15 In the embodiment as shown in Figure 9, the aperture device 330 includes an array of pinholes 332 similar to the pinholes 222 of the pinhole device 220. The aperture device 330 may further include an array of microlenses 334 arranged with the array of pinholes 332, similar to the microlenses 224 of the pinhole device 220. Specifically, the aperture device 330 includes the array of microlenses 334 arranged in front of the
20 pinholes 332, i.e. between the beam splitter 210 and the pinholes 332, such that each pinhole 332 is associated with a microlens 334 of the array. The pinholes 332 and microlenses 334 arrays may be formed separately and coupled together, or they may be integrated together as a single unit. Each pinhole 332 is paired with one microlens 334 and they cooperate to focus light into the centre of the respective pinhole 332.

25

In summary, in the embodiment as shown in Figure 9, the apparatus 20 includes the light source assembly 100, confocal microscopy assembly 200, and optical detection assembly 300 being a one-shot hyperspectral imaging assembly 302 configured for measuring the surface profile and subsurface profile including multi-layer film
30 thickness of the object 30. The light source assembly 100 includes the broadband

light source 110 and the Köhler illumination device 120. The confocal microscopy assembly 200 includes the beam splitter 210 and the pinhole device 220 having the array of pinholes 222 and one or more arrays of microlenses 224 arranged with the array of pinholes 222. The confocal microscopy assembly 200 further includes the set
5 of incident optical elements 230 and the actuation mechanism 240 for planarly moving the pinhole device 220 along the X-axis and Y-axis. However, the apparatus 20 may exclude or stop the actuation mechanism 240 to perform quick sampling measurement of the object 30. The incident optical elements 230 include the objective lens 232, tube lens 234, and chromatic aberration lens 236. The one-shot
10 hyperspectral imaging assembly 302 includes the optical detector 310 having the hyperspectral camera 314, the aperture device 330 including an array of pinholes 332 and an array of microlenses 334 arranged with the array of pinholes 332, and the wavelength differentiation device 340. The one-shot hyperspectral imaging assembly 302 further includes the set of detection optical elements 320 having the relay lens
15 326, collimator 324, and imaging lens 322.

In the embodiments as shown in Figures 1 and 9, the apparatus 20 is configured to scan 2D areas of the surface profile of the object 30. Specifically, the array of pinholes 222 of the pinhole device 220 are arranged across a 2D plane. In one embodiment as
20 shown in Figure 11, the apparatus 20 is configured to perform line scanning of the surface profile of the object 30. It will be appreciated that various aspects described above for the embodiments of Figures 1 and 9 will apply similarly or analogously to the embodiment of Figure 11, and vice versa. In the embodiment of Figure 11, instead of a 2D array of pinholes 222, the pinholes 222 and likewise the microlenses 224 are
25 arranged in a single row (1D line). Similarly for the aperture device 330, instead of a 2D array of pinholes 332, the pinholes 332 and likewise the microlenses 334 are arranged in a single row (1D line). Alternatively, the single row of pinholes 332 may be replaced by a 1D slit aperture 336 as shown in Figure 11.

Additionally, the optical aperture 114 of the broadband light source 110 is a line aperture to correspond to the single rows of pinholes 222 / 332. The Köhler illumination device 120 is also replaced by a cylindrical lens 122 which focuses the broadband light beam to a line light. The actuation mechanism 240 for planarly moving the pinhole device 220 may be configured to move the pinhole device 220 in a direction parallel to the single row of pinholes 222 to cover gaps or pitches between the pinholes 222. For example, the row of pinholes 222 extends along the X-axis across the surface profile and the actuation mechanism 240 is configured to move the pinhole device 220 along the X-axis. The actuation mechanism 240 is cooperative with the displaceable table supporting the object 30 to measure the whole surface profile of the object 30. For example, the actuation mechanism 240 moves the pinholes 222 along the X-axis while the table moves the object 30 along the Y-axis. The optical detector 310 (such as the colour camera 312 or hyperspectral camera 314) captures a row of spectrum at a time as the line light moves across the surface profile. Figure 12 an example of a hyperspectral image 60 of the object 30 captured by the hyperspectral camera 314 in successive rows of spectrum.

In summary, in the embodiment as shown in Figure 11, the apparatus 20 is configured for line scanning the object 30 and includes the light source assembly 100, confocal microscopy assembly 200, and optical detection assembly 300 being the one-shot hyperspectral imaging assembly 302. The light source assembly 100 includes the broadband light source 110 and the cylindrical lens 122 for focusing the uniform light from the broadband light source 110 into a line light for line scanning the object 30. The confocal microscopy assembly 200 includes the beam splitter 210 and the pinhole device 220 having the array of pinholes 222 in a single row for the line scanning and one or more arrays of microlenses 234 arranged with the row of pinholes 222. The confocal microscopy assembly 200 further includes the set of incident optical elements 230 and the actuation mechanism 240 for planarly moving the pinhole device 220 parallel to the row of pinholes 222, e.g. along the X-axis. The incident optical elements 230 include the objective lens 232, tube lens 234, and

chromatic aberration lens 236. The one-shot hyperspectral imaging assembly 302 includes the optical detector 310 having the hyperspectral camera 314, the aperture device 330 having the slit aperture 336 for the line scanning, and the wavelength differentiation device 340. Alternatively, the aperture device 330 includes a single row of pinholes 332 for the line scanning and a single row of microlenses 334 arranged with the row of pinholes 332. The one-shot hyperspectral imaging assembly 302 further includes the set of detection optical elements 320 having the relay lens 326, collimator 324, and imaging lens 322.

10 In one embodiment as shown in Figure 13, the apparatus 20 is substantially similar to the embodiment as shown in Figure 9 except for the pinhole device 220. However, it will be appreciated that various aspects described above for the embodiments of Figures 1, 9, and 11 will apply similarly or analogously to the embodiment of Figure 13, and vice versa. In the embodiment of Figure 13, the pinhole device 220 is in the form of a Nipkow disk 226. The Nipkow disk 226 is a scanning disk having the pinholes 222 which may be equal-distanced and circular or squarish. The actuation mechanism 240 is configured to planarly rotate the Nipkow disk 226 around the Z-axis. Preferably, the pinholes 222 are positioned to form a single-turn spiral starting from an external radial point of the Nipkow disk 226 and towards the centre, such that the pinholes 222 trace circular ring patterns when the actuation mechanism 240 rotates the Nipkow disk 226. As described above, when the Nipkow disk 226 rotates, the pinholes 222 and corresponding points on the surface profile of the object 30 are moved across it, enabling a continuous surface area of the surface profile to be scanned and measured.

25

In one embodiment as shown in Figure 14, the Nipkow disk 226 further includes a first array of microlenses 224 arranged on top of the pinholes 222. As shown in Figure 15, the Nipkow disk 226 may further include a second array of microlenses 224 arranged below the pinholes 222, i.e. the array of pinholes 222 is sandwiched between the first

and second arrays of microlenses 224. Each pinhole 222 is associated with at least one microlens 224 configured for focusing light into the respective pinhole 222.

In summary, in the embodiments as shown in Figures 13 to 15, the apparatus 20 includes the light source assembly 100, confocal microscopy assembly 200, and optical detection assembly 300 being the one-shot hyperspectral imaging assembly 302. The light source assembly 100 includes the broadband light source 110 and the Köhler illumination device 120. The confocal microscopy assembly 200 includes the beam splitter 210 and the pinhole device 220 in the form of the Nipkow disk 226 having the array of pinholes 222. The Nipkow disk 226 may further include one or more arrays of microlenses 224 arranged with the array of pinholes 222. The confocal microscopy assembly 200 further includes the set of incident optical elements 230 and the actuation mechanism 240 for rotating the pinhole device 220 along the Z-axis. The incident optical elements 230 include the objective lens 232, tube lens 234, and chromatic aberration lens 236. The one-shot hyperspectral imaging assembly 302 includes the optical detector 310 having the hyperspectral camera 314, the aperture device 330 having an array of pinholes 332 and an array of microlenses 334 arranged with the array of pinholes 332, and the wavelength differentiation device 340. The one-shot hyperspectral imaging assembly 302 further includes the set of detection optical elements 320 having the relay lens 326, collimator 324, and imaging lens 322.

In one embodiment as shown in Figure 16, the apparatus 20 includes the light source assembly 100, confocal microscopy assembly 200, and optical detection assembly 300 as described above. The light source assembly 100 includes the broadband light source 110 and Köhler illumination device 120. The optical detection assembly 300 includes the colour camera 312 and the imaging lens 322, although it will be appreciated that the optical detection assembly 300 can be the one-shot hyperspectral imaging assembly 302.

The confocal microscopy assembly 200 includes the beam splitter 210, the pinhole device 220 in the form of the Nipkow disk 226, and the actuation mechanism 240 for rotating the Nipkow disk 226. The confocal microscopy assembly 200 further includes the tube lens 234, chromatic aberration lens 236, and objective lens 232 cooperative
5 for chromatically aberrating and focusing light on the object 30. The object 30 is supported on a table 32 that is configured to be displaceable. For example, the table 32 is coupled to or integrated with actuators, such as motors and piezoelectric actuators, that can displace the table 32 along and/or rotate the table 32 around at least one of the XYZ-axes.

10

In some embodiments such as shown in Figure 16, the incident optical elements 230 include a first objective lens 232 and a second objective lens 238. The confocal microscopy assembly 200 further includes switching device or turret 250 for supporting the first and second objective lenses 232,238. The switching device 250
15 may include actuators, such as motors and piezoelectric actuators, and can be operated to switch between the objective lenses 232,238. For example, the first objective lens 232 has higher magnification power while the second objective lens 238 has lower magnification power. Although two objective lenses 232,238 are described, it will be appreciated that the incident optical elements 230 may include
20 multiple objective lenses switchable between each other using the turret 250, wherein the objective lenses may be of varying magnification powers so that measurement performance can be selected accordingly.

Although the 3D surface profile measurement apparatus 20 can mainly be used for
25 online high speed measurements and inspection, it can also be used as a standalone measurement system for sampling measurements. As an example, the Figure 16 shows a standalone example of the measurement apparatus 20.

As mentioned before, the apparatus 20 includes the broadband light source 110,
30 illumination device 120, and the beam splitter 210, which directs the uniform

illumination light to the surface of the Nipkow disk 226. Some of the light is blocked by the Nipkow disk 226 and some of the light passes through the pinholes 222 of the Nipkow disk 226. The light from the pinholes 222 passes through tube lens 234, chromatic aberration lens 236 and finally is focused by the objective lens 232 on the
5 surface of the object 30 mounted on the mechanical displaceable table 32.

An observation device 500 is inserted between the objective lens 232 and tube lens 234 for observation and selecting of the area of the surface profile for inspection. The observation device 500 includes a first beam splitter 510, a second beam splitter 520,
10 an ocular lens or eyepiece 530, an imaging lens 540, and a camera 550. The surface profile of the object 30 is imaged by the objective lens 232 and reflected by the first beam splitter 510 and second beam splitter 520. The image can be imaged by the imaging lens 540 and camera 550. The image of the object 30 is also can be observed directly through the eyepiece 530 by the naked eye. The observation device
15 500 can moved in for observation and moved out for the 3D surface profile measurements.

As described in various embodiments above, the apparatus 20 and method 400 can measure the surface profile of the object 30 by capturing a single image of the surface
20 profile and using spectral analysis to generate the surface topography of the object 30. The light source assembly 100 provides uniform broadband light to the confocal microscopy assembly 200 and optical detection assembly 300 to image the object 30. The confocal microscopy assembly 200 generates and collects spectral information of the surface profile, and the optical detection assembly 300 records the spectral
25 information on a spectral image of the surface profile. The apparatus 20 can be integrated or coupled with an image processing module to generate the surface topography of the object 30 based on the spectral image, such as the spectral image 40 or hyperspectral image 50 mentioned above. For example, with the hyperspectral image 50, subsurface topography and surface layer thicknesses of the object 30 can
30 be inspected in addition to the surface topography.

The spectral analysis is based on the principle of chromatic aberration of the broadband uniform light as it passes through the confocal microscopy assembly 200. The chromatic aberration of the uniform light creates spectral information with more
5 distinct wavelengths that are representative of the heights across the surface profile, and the surface profile can be measured accurately based on these wavelengths without vertical scanning. Compared to conventional point-by-point measurements which are slow, the apparatus 20 can achieve high-speed surface profile measurements because of the pinhole device 220, such as the Nipkow disk 226. The
10 whole surface profile can be scanned and measured without any gaps, thereby mitigating risk of excluding relevant regions of interest and allowing for higher quality inspection of the object 30.

Therefore, the apparatus 20 and method 400 can be used for high-speed and
15 accurate measurement of the surface profile, especially if the surface profile is undulating or discontinuous. This would be suitable in various applications, including for high-speed automatic surface topography inspection of semiconductor wafers, integrated circuit wire loops, and precision components.

20 In the foregoing detailed description, embodiments of the present disclosure in relation to the apparatus 20 and method 400 for measuring the surface profile of the object are described with reference to the provided figures. The description of the various embodiments herein is not intended to call out or be limited only to specific or particular representations of the present disclosure, but merely to illustrate
25 non-limiting examples of the present disclosure. The present disclosure serves to address at least one of the mentioned problems and issues associated with the prior art. Although only some embodiments of the present disclosure are disclosed herein, it will be apparent to a person having ordinary skill in the art in view of this disclosure that a variety of changes and/or modifications can be made to the disclosed
30 embodiments without departing from the scope of the present disclosure. Therefore,

the scope of the disclosure as well as the scope of the following claims is not limited to embodiments described herein.

Claims

1. An apparatus for measuring a surface profile of an object, the apparatus comprising:
- 5 a light source assembly comprising a broadband light source;
 a confocal microscopy assembly comprising:
 a beam splitter for directing uniform light from the
 broadband light source to the object;
 a pinhole device comprising an array of pinholes, the
10 pinhole device configured for passing the uniform light from the
 beam splitter through the pinholes to the object;
 a set of incident optical elements for directing the uniform
 light from the pinhole device to the object and causing chromatic
 aberration of the uniform light passing through the incident
15 optical elements; and
 the pinhole device configured for passing light reflected
 from the object through the pinholes to the beam splitter, the
 reflected light comprising spectral information of the surface
 profile based on the chromatic aberration; and
20 an optical detection assembly comprising:
 an optical detector for receiving the reflected light from the
 beam splitter; and
 a set of detection optical elements for directing the
 reflected light from the beam splitter to the optical detector,
25 wherein the surface profile of the object is measurable based on
 spectral information of the reflected light received by the optical detector,
 the spectral information representing heights across the surface profile.
2. The apparatus according to claim 1, wherein the broadband light source
30 comprises:

an optical integrating sphere;
a set of light lamps arranged around the optical integrating
sphere configured to integrate light energy from the light lamps; and
an optical aperture for directing the uniform light emitted from the
5 light lamps out of the broadband light source.

3. The apparatus according to claim 2, wherein the light lamps are white light
elements configured for emitting light ranging from red to blue or from infrared
to ultraviolet.

10

4. The apparatus according to any one of claims 1 to 3, wherein the pinhole
device comprises one or more arrays of microlenses arranged with the array of
pinholes, such that each pinhole is associated with at least one microlens
configured for focusing light from the beam splitter into the respective pinhole.

15

5. The apparatus according to claim 4, wherein the arrays of microlenses are
arranged on one or both sides of pinhole device.

6. The apparatus according to any one of claims 1 to 5, wherein the confocal
20 microscopy assembly comprises an actuation mechanism for planarly moving
the pinhole device.

7. The apparatus according to claim 6, wherein the actuation mechanism is
configured for planarly moving the pinhole device along the X-axis and/or
25 Y-axis.

8. The apparatus according to any one of claims 1 to 7, wherein the set of
incident optical elements comprises:

an objective lens for focusing light on the object;

a tube lens for focusing the reflected light from the object on the pinhole device; and

a chromatic aberration lens disposed between the tube lens and objective lens for causing the chromatic aberration of the light.

5

9. The apparatus according to claim 8, wherein the objective lens and chromatic aberration lens are integrated as a single lens element.

10. The apparatus according to any one of claims 1 to 9, wherein the optical
10 detection assembly is a hyperspectral imaging assembly configured for measuring the surface profile and subsurface profile of the object.

11. The apparatus according to claim 10, wherein the hyperspectral imaging
assembly is a one-shot hyperspectral imaging assembly configured for
15 measuring the surface profile and subsurface profile of the object in a single image.

12. The apparatus according to claim 11, wherein the one-shot hyperspectral imaging assembly comprises:

20 the optical detector comprising a hyperspectral camera;
an aperture device for passing through the reflected light from beam splitter to the hyperspectral camera; and
a wavelength differentiation device disposed between the aperture device and the hyperspectral camera for differentiating the
25 reflected light; and
the set of detection optical elements comprising:
a relay lens disposed between the beam splitter and aperture device;
a collimator disposed between the aperture device and
30 wavelength differentiation device; and

an imaging lens disposed between the wavelength differentiation device and hyperspectral camera for focusing the reflected light on the hyperspectral camera.

5 13. The apparatus according to claim 12, wherein the aperture device comprises an array of pinholes or a slit aperture.

14. The apparatus according to claim 13, wherein the aperture device comprises the array of pinholes and an array of microlenses arranged with the
10 array of pinholes, such that each pinhole is associated with one microlens configured for focusing the reflected light from the beam splitter into the respective pinhole.

15. The apparatus according to any one of claims 12 to 14, wherein the
15 wavelength differentiation device comprises an optical grating for diffracting the reflected light or an optical prism for dispersing the reflected light.

16. The apparatus according to claim 1,
the light source assembly comprising the broadband light source
20 and an illumination device for uniformly directing the uniform light from the broadband light source;

the confocal microscopy assembly comprising:

the beam splitter and the set of incident optical elements;

the pinhole device comprising the array of pinholes and
25 one or more arrays of microlenses arranged with the array of pinholes, such that each pinhole is associated with at least one microlens configured for focusing light from the beam splitter into the respective pinhole; and

an actuation mechanism for planarly moving the pinhole
30 device along the X-axis and Y-axis; and

the optical detection assembly comprising a colour camera for measuring the surface profile of the object.

17. The apparatus according to claim 1,

5 the light source assembly comprising the broadband light source and an illumination device for uniformly directing the uniform light from the broadband light source;

the confocal microscopy assembly comprising:

the beam splitter and the set of incident optical elements;

10 and

the pinhole device comprising the array of pinholes and one or more arrays of microlenses arranged with the array of pinholes, such that each pinhole is associated with at least one microlens configured for focusing light from the beam splitter into the respective pinhole; and

15

the optical detection assembly being a one-shot hyperspectral imaging assembly configured for measuring the surface profile and subsurface profile of the object, the one-shot hyperspectral imaging assembly comprising:

20 a hyperspectral camera; and

an aperture device for passing through the reflected light from beam splitter to the hyperspectral camera, the aperture device comprising an array of pinholes and an array of microlenses arranged with the array of pinholes, such that each pinhole is associated with one microlens configured for focusing the reflected light from the beam splitter into the respective pinhole.

25

18. The apparatus according to claim 17, an actuation mechanism for planarly moving the pinhole device along the X-axis and Y-axis

30

19. The apparatus according to claim 1,
- the light source assembly comprising the broadband light source and a cylindrical lens for focusing the uniform light from the broadband light source into a line light for line scanning the object;
 - the confocal microscopy assembly comprising:
 - the beam splitter and the set of incident optical elements;
 - the pinhole device comprising the array of pinholes in a single row for the line scanning and one or more arrays of microlenses arranged with the row of pinholes, such that each pinhole is associated with at least one microlens configured for focusing light from the beam splitter into the respective pinhole;
 - and
 - an actuation mechanism for planarly moving the pinhole device parallel to the row of pinholes; and
 - the optical detection assembly being a one-shot hyperspectral imaging assembly configured for measuring the surface profile and subsurface profile of the object, the one-shot hyperspectral imaging assembly comprising:
 - a hyperspectral camera; and
 - an aperture device for passing through the reflected light from beam splitter to the hyperspectral camera, the aperture device comprising a single row of pinholes for the line scanning and a single row of microlenses arranged with the row of pinholes, such that each pinhole is associated with one microlens configured for focusing the reflected light from the beam splitter into the respective pinhole.

20. The apparatus according to claim 1,

the light source assembly comprising the broadband light source and a cylindrical lens for focusing the uniform light from the broadband light source into a line light for line scanning the object;

the confocal microscopy assembly comprising:

5 the beam splitter and the set of incident optical elements;
 the pinhole device comprising the array of pinholes in a single row for the line scanning and one or more arrays of microlenses arranged with the row of pinholes, such that each pinhole is associated with at least one microlens configured for
10 focusing light from the beam splitter into the respective pinhole;
 and

 an actuation mechanism for planarly moving the pinhole device parallel to the row of pinholes; and

 the optical detection assembly being a one-shot hyperspectral
15 imaging assembly configured for measuring the surface profile and subsurface profile of the object, the one-shot hyperspectral imaging assembly comprising:

 a hyperspectral camera; and

 an aperture device for passing through the reflected light
20 from beam splitter to the hyperspectral camera, the aperture device comprising a slit aperture for the line scanning.

21. The apparatus according to claim 1,

 the light source assembly comprising the broadband light source
25 and an illumination device for uniformly directing the uniform light from the broadband light source;

 the confocal microscopy assembly comprising:

 the beam splitter and the set of incident optical elements;
 the pinhole device in the form of a Nipkow disk comprising
30 the array of pinholes; and

an actuation mechanism for rotating the pinhole device
along the Z-axis; and

the optical detection assembly being a one-shot hyperspectral
imaging assembly configured for measuring the surface profile and
subsurface profile of the object, the one-shot hyperspectral imaging
assembly comprising:

a hyperspectral camera; and

an aperture device for passing through the reflected light
from beam splitter to the hyperspectral camera, the aperture
device comprising an array of pinholes and an array of
microlenses arranged with the array of pinholes, such that each
pinhole is associated with one microlens configured for focusing
the reflected light from the beam splitter into the respective
pinhole.

22. The apparatus according to claim 21, wherein the Nipkow disk further
comprises one or more arrays of microlenses arranged with the array of
pinholes, such that each pinhole is associated with at least one microlens
configured for focusing light from the beam splitter into the respective pinhole.

23. The apparatus according to claim 22, wherein the arrays of microlenses
are arranged on one or both sides of pinhole device.

24. The apparatus according to any one of claims 21 to 23, wherein the
pinholes are circular or squarish.