(12) INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(19) World Intellectual Property Organization
International Bureau

(43) International Publication Date
09 January 2025 (09.01.2025)

WIPO | PCT

(10) International Publication Number
WO 2025/008656 A1

(51) International Patent Classification:
G01N 21/95 (2006.01) *G01N 21/88* (2006.01)
H01L 21/66 (2006.01)

(21) International Application Number: PCT/IB2023/000459

(22) International Filing Date: 06 July 2023 (06.07.2023)

(25) Filing Language: English

(26) Publication Language: English

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(81) Designated States *(unless otherwise indicated, for every kind of national protection available)*: AE, AG, AL, AM, AO, AT, AU, AZ, BA, BB, BG, BH, BN, BR, BW, BY, BZ, CA, CH, CL, CN, CO, CR, CU, CV, CZ, DE, DJ, DK, DM, DO, DZ, EC, EE, EG, ES, FI, GB, GD, GE, GH, GM, GT, HN, HR, HU, ID, IL, IN, IQ, IR, IS, IT, JM, JO, JP, KE, KG, KH, KN, KP, KR, KW, KZ, LA, LC, LK, LR, LS, LU, LY,

(54) Title: DEVICE FOR INSPECTING SUBSTRATES

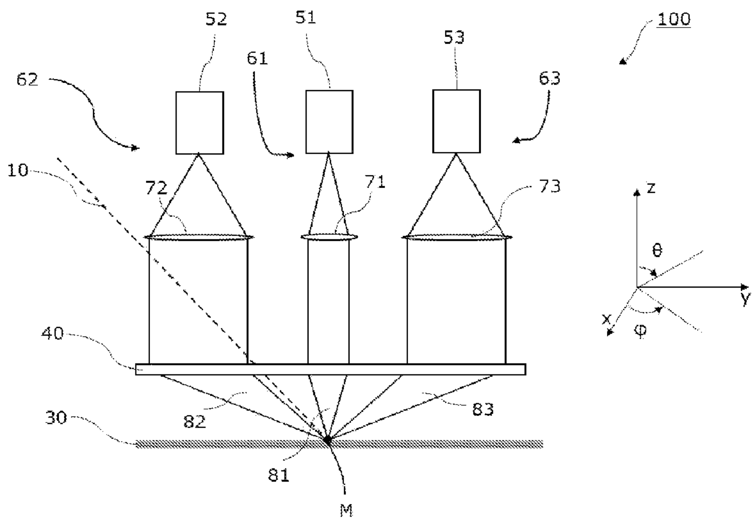

Fig. 3

(57) Abstract: The invention relates to an inspection device (100, 200, 300, 400, 500) for detecting defects on substrates, such as wafers, comprising : - an illumination module (10) comprising at least one light source (12) configured to illuminate at least one region of a substrate (30) to be inspected with at least one illumination beam (20, 21); - at least one detector (51, 52, 53, 54, 54-1, 54-2, 55, 55-1, 55-2, 56-1, 56-2) configured to detect light issued from the substrate (30) and to produce an inspection signal; - a light collection module; and - a processing module configured to produce an inspection information from the inspection signal, wherein the light collection module comprises at least one collection lens (40) with a nanostructured surface (90), the nanostructured surface (90) comprising at least one light collection region (91, 92, 92', 93, 94, 95, 96, 97, 98) configured to collect light issued from the substrate (30) within a predetermined solid angle (81, 82, 83, 84, 85) and to direct the collected light towards a corresponding detector (51, 52,

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[Continued on next page]

MA, MD, MG, MK, MN, MU, MW, MX, MY, MZ, NA, NG, NI, NO, NZ, OM, PA, PE, PG, PH, PL, PT, QA, RO, RS, RU, RW, SA, SC, SD, SE, SG, SK, SL, ST, SV, SY, TH, TJ, TM, TN, TR, TT, TZ, UA, UG, US, UZ, VC, VN, WS, ZA, ZM, ZW.

(84) Designated States *(unless otherwise indicated, for every kind of regional protection available)*: ARIPO (BW, CV, GH, GM, KE, LR, LS, MW, MZ, NA, RW, SC, SD, SL, ST, SZ, TZ, UG, ZM, ZW), Eurasian (AM, AZ, BY, KG, KZ, RU, TJ, TM), European (AL, AT, BE, BG, CH, CY, CZ, DE, DK, EE, ES, FI, FR, GB, GR, HR, HU, IE, IS, IT, LT, LU, LV, MC, ME, MK, MT, NL, NO, PL, PT, RO, RS, SE, SI, SK, SM, TR), OAPI (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, KM, ML, MR, NE, SN, TD, TG).

Published:

— *with international search report (Art. 21(3))*

53, 54, 54-1, 54-2, 55, 55-1, 55- 2, 56-1, 56-2), a light collection region and a corresponding detector forming a collection channel (61, 62, 63, 64, 65, 66, 67, 68).

Device for inspecting substrates

Field of the invention

[0001] The present invention relates to a device for inspecting substrates, such as semiconductor wafers.

[0002] The field of the invention is the field of the inspection, characterization, and quality control of substrates, such as semiconductor wafers.

Background

[0003] Inspection devices or defect detection devices are used to characterize samples such as semiconductor substrates, or wafers, in particular during fabrication. Defects include, for example, pits and particles, such as metal particles. Defects can also include, for example, crystalline defects inducing photoluminescence.

[0004] A dark-field light collection architecture of an inspection device of the prior art is illustrated in FIGURE 1. A dashed line 10 indicates an illumination beam. In the illustrated example, the device 1 comprises two or three optical radiation collection channels. A narrow-angle collection channel with a collection lens 3 detects light issued from the illumination area M in a solid angle close to the normal z of the substrate 2, for example between 0 to 0.095 sr, corresponding to 0° - 10° (degree) in plane angles. A wide-angle collection channel with a collection mirror 4 detects light at wide solid angles with respect to the normal z, for example corresponding to 60° - 89° plane angles. The wide-angle collection channel may further be split in two channels, a forward detection channel in the direction of the forward scattering of the light issued from the illumination area, and a backward detection channel in the direction of the backward scattering. The device comprises one detector 6 for the narrow-angle detection, and one or two further detectors 7 for the wide-angle detection.

[0005] In the illustrated example, the device 1 is in a dark-field configuration for the detection of the scattered light. The collection channels are indeed arranged to avoid collecting light of specular reflections from the substrate 2.

[0006] The collection channels convey light from a detection area. In the example of FIGURE 1, the detection area is located around the illumination area M. The detection area can be identical or different for the respective collection channels. In the example of FIGURE 1, the device 1 comprises a collection fiber bundle 5. The detection area of the respective collection channels can then be defined as an optical conjugate of the core of the respective fibers 5 by the optical system of the collection channel. The light is then guided by the fibers 5 towards the detectors.

[0007] However, the device 1 uses bulky components, such as the collection mirrors, that have to be able to collect the light notably under the wide solid angles. Such components have several drawbacks, including, but not limited to, bulkiness, inflexibility, non-versatility, and cost of fabrication.

[0008] In particular, it is difficult to design them such as they may be used for collecting light under extremely narrow and wide solid angles, or under many different solid angles. Also, the collection optics collects indistinctively all the light, including scattered light and photoluminescence light, regardless of the polarization of this radiation. If a better selectivity is sought, it has to be added afterwards by splitting the channels with polarizers and/or spectral filters, leading to complex architectures.

Summary of the invention

[0009] A purpose of the present invention is to overcome at least one of the drawbacks of the known techniques.

[0010] Another purpose of the present invention is to provide an inspection device combining several light collection functions in a compact, flexible, versatile, and cost effective manner.

[0011] At least one of these aims is achieved by an inspection device for detecting defects on substrates, such as wafers, comprising:

- an illumination module comprising at least one light source configured to illuminate at least one region of a substrate to be inspected with at least one illumination beam;
- at least one detector configured to detect light issued from the substrate and to produce an inspection signal;
- a light collection module; and
- a processing module configured to produce an inspection information from the inspection signal,

wherein the light collection module comprises at least one collection lens with a nanostructured surface, the nanostructured surface comprising at least one light collection region configured to collect light issued from the substrate within a predetermined solid angle and to direct the collected light towards a corresponding detector, a light collection region and a corresponding detector forming a collection channel.

[0012] The inspection device according to the present invention comprises a light collection lens with a nanostructured surface. Such a nanostructured surface comprises subwavelength-scale elements and allows for wavefront shaping of incident light. These surfaces are also called metasurfaces. In the present invention, a metasurface is used to realize a collection lens, called metalens. The collection lens combines several functions, namely the collection of light issued from the substrate to be inspected according to at least one specific solid angle, and the redirection of the collected light into a given direction of light, depending on said solid collection angle. For this, the metasurface comprises at least one collection region, or section, characterized by a specific subwavelength-scale pattern. In the current description, a solid angle is defined as an angular sector in a tridimensional coordinate system, such as a range of polar and azimuthal angles in a spherical coordinate system.

[0013] As it is known in the prior art, the spatial distribution of scattered light from defects depends notably on their nature. For example, in the Rayleigh regime and for a P polarized illumination beam, a pit scatters light in a narrow solid angle (0° to ~18°) contrary to a small particle which scatters in a wide solid angle (~53° to ~85°). By collecting these two distributions of scattered light in two different channels, pits and particles may be easily discriminated.

[0014] The inspection device according to the present invention therefore advantageously replaces a plurality of bulky components, executing the function of collecting and redirecting the light, of a device of the prior art, such as a refractive lens for narrow solid angle collection, or a parabolic mirror for wide solid angle collection. It offers a compact, single-element solution for the light collection and guidance in at least one desired solid angle.

[0015] Consequently, the size and the cost of the inspection device may be considerably reduced by implementing a collection lens having a metasurface, or a collection metalens. The functionalities of the device may be readily defined and realized by the appropriate design of the metasurface. One or more collection channels may be implemented in the device tailoring it to its desired application, such as improved selectivity by collecting light under well-defined solid angles, maximized signal-to-noise ratio (SNR) in different applications, etc. Complex arrangements of the collection region(s) are possible.

[0016] The collection lens is made with materials that are adapted for an optimized transmission of the illumination beam(s) wavelength, and more generally any wavelength of interest.

[0017] The substrates to be inspected may comprise, for instance, silicon wafers, glass carrier wafers, or compound wafers such as silicon carbide (SiC) wafers. They may also comprise other shapes of substrate such as flat panels. These substrates can comprise bulk materials (silicon, glass), layered materials (SiC with epitaxial layers), or patterned, stacked, or composite substrates (molded substrates), at any step of process in the manufacturing of semiconductor elements, such as electronic components.

[0018] The collected light can include scattered, diffracted, and/or reflected light at the illumination wavelength. The collected light may also include photoluminescence radiation, for example due to fluorescence, at wavelength different from the illumination wavelength.

[0019] The different types of signals are processed separately and/or simultaneously.

[0020] Several types of detectors may be used, such as photomultipliers, photodiodes, avalanche photodiodes, line or matrix detectors, cameras, and the like. The detectors may be arranged in form of unique detectors or arrays of detectors.

[0021] The detectors may also comprise spectrometers allowing to analyse the optical spectrum of the collected light, in particular for photoluminescence radiation.

[0022] According to an embodiment, the inspection device may comprise at least two collection channels, the collection channels corresponding to different solid angles.

[0023] Two or more collection channels allow for instance discrimination of different types of defects on the substrate, according to the solid angle of the scattered light.

[0024] According to an embodiment, the collection channel may comprise a plurality of polarization sub-channels, each corresponding to a different polarization of the light issued from the substrate, the light of each polarization sub-channel being directed in a different direction.

[0025] With this configuration, the inspection device according to the present invention allows for obtaining a combined spatial and polarization dependent information and therefore an efficient identification and discrimination of defects. Polarization dependent scattering characteristics of the defects may be detected, thus providing a more comprehensive information on the surface of the substrate. For example, the polarization characteristics of the light scattered by the micro-roughness of the substrate’s surface, also known as haze, are different from those of light scattered by other types of defects such as pits and particles. Thus, by discriminating or selecting specific polarizations in the collection by means of the polarization sub-channels, the SNR of the inspection signals may be improved.

[0026] Thanks to the nanostructured surface, no additional polarizers are necessary in the collection part of the inspection device.

[0027] Advantageously, the polarization sub-channels may be implemented by a birefringent nanostructured surface of the collection lens.

[0028] According to an embodiment, the collection channel may comprise a plurality of chromatic sub-channels, each corresponding to a different spectral range of the light issued from the substrate, the light of each chromatic sub-channel being directed in a different direction.

[0029] This configuration is particularly useful to analyse light issued from photoluminescence within the substrate in different spectral bands.

[0030] Advantageously, the chromatic sub-channels may be implemented by a chromatic nanostructured surface of the collection lens.

[0031] According to an embodiment, the collection lens may comprise a region without nanostructures such that the illumination light passes through that region of the collection lens without modulation to illuminate the substrate. Alternatively, especially considering small incident angles, the region where the incident illumination is transmitted through the collection lens may be tailored to engineer the incident beam profile, notably by featuring specific subwavelength-scale structures.

[0032] According to an embodiment, the illumination module and the at least one detector may be configured to operate in a dark-field configuration.

[0033] Thanks to the dark-field configuration, the specular reflection of the illumination beam or beams on the surface of the substrate does not reach the detectors, allowing for an increased SNR when detecting scattered, diffracted, or photoluminescence light.

[0034] In particular, when collecting photoluminescence light, such as fluorescence light, the dark-field conditions avoid having intense illumination light arriving at the detectors.

[0035] Alternatively, the illumination module and the at least one detector may be configured to operate in a bright-field configuration.

[0036] In this case, the light due to specular reflection on the surface of the substrate is detected, as well as the scattered or diffracted light. These signals may provide information on the structure or the shape of the surface.

[0037] Advantageously, the collection module may comprise a focusing lens for each collection channel configured to focus the collected light on the detector, the at least one light collection region being configured for collimating the collected light.

[0038] Alternatively, the at least one light collection region may be configured to focus the collected light on the detector.

[0039] This configuration allows for a particularly compact inspection device.

[0040] According to an embodiment, the inspection device according to the invention may further comprise displacement means configured to displace the illuminated region on the substrate.

[0041] The displacement means may move the substrate to be inspected with respect to the light collection module.

[0042] According to an example, an angle of incidence of the illumination beam on the substrate may vary between grazing incidence and normal incidence, depending on the scattering or photoluminescence properties of interest.

[0043] In particular, the angle of incidence may vary between less than 90°, for example, 80°, and normal incidence, i.e., 0°.

[0044] More particularly, the angle of incidence can be within the ranges 30° - 75°, or 45° - 60°.

[0045] Advantageously, at least two illumination beams may intersect each other in the illuminated region on the substrate.

[0046] According to an example, the light issued from the light source is split to form two converging beams intersecting each other on the substrate, or at a pre-defined depth in the substrate. The beams may cross each other with an angle between them of 10° to 45° for instance, or more specifically 15° to 30°.

[0047] These two beams may be contained within an illumination plane forming an angle of incidence, with the normal of the surface of the substrate, which can be of any value from a grazing incidence (less than 90°, for example 80°) to a normal incidence (0°). More specifically, the angle of incidence can be within the ranges 30° - 75°, or 45° - 60°.

[0048] According to an example, two illumination beams may form an interference pattern in the illuminated region.

[0049] To achieve this, the two illumination beams must be coherent with each other. When the illuminated region with the interference pattern is moved on the substrate and a scattering element is illuminated, the inspection signal detected from the substrate is modulated. The modulation of the inspection signal improves the SNR and the precision of the spatial localization, in particular in depth, of the scattering, diffracting, or fluorescent element.

<u>Description of the figures and embodiments</u>

[0050] Other advantages and characteristics will become apparent on examination of the detailed description of an embodiment which is in no way limitative, and the attached figures, where:

- FIGURE 1 is a schematical representation of an inspection device of the prior art;

- FIGURE 2 is a schematical representation of an illumination module implemented with the inspection device according to an embodiment of the present invention;
- FIGURES 3 to 7 are schematical representations of non-limitative examples of inspection devices according to the present invention; and
- FIGURE 8 shows schematical illustrations of a nanostructured surface implemented with the inspection device according to embodiments of the present invention.

[0051] It is well understood that the embodiments that will be described below are in no way limitative. In particular, it is possible to imagine variants of the invention comprising only a selection of the characteristics described hereinafter, in isolation from the other characteristics described, if this selection of characteristics is sufficient to confer a technical advantage or to differentiate the invention with respect to the state of the prior art.

[0052] In the FIGURES, elements common to several figures may keep the same reference.

[0053] An inspection device according to the present invention comprises an illumination module with at least one light source producing at least one illumination beam for illuminating a region of a substrate to be inspected. It further comprises at least one detector in order to detect light issued from the substrate and to produce an inspection signal. A light collection module of the inspection device comprises at least one collection lens with a nanostructured surface, a so-called metalens. The nanostructured surface has at least one light collection region for collecting light issued from the substrate within a predetermined solid angle and for directing the collected light towards a corresponding detector. A processing module may then produce an inspection information from the inspection signal.

[0054] FIGURE 2 is a schematical representation of an example of an illumination module of an inspection device according to the present invention.

[0055] The illumination module 10, represented in FIGURE 2, comprises a light source 12 coupled to an optical fiber 14. The fiber 14 is split by a beam splitter 15 into to fibers 16, 17 equipped with collimators 18, 19 at their far ends in order to form two converging illumination beams 20, 21. The beams 20, 21 cross each other on the substrate 30 to be inspected. The beams 20, 21 may also cross each other at a pre-defined depth in the substrate 30. The illuminated region on or in the substrate 30 defines a measurement zone M.

[0056] The light source 12 may comprise any kind of light source, such as laser, light-emitting diode (LED), arc or gas discharge lamp, or laser-driven plasma light source, etc.

[0057] In the illustrated example, the substrate 30 to be inspected is held on a chuck 22, or a holder. The chuck 22 can be rotated around a rotation axis *r* and translated radially in the x-y plane such that the measurement zone M is scanned over the whole surface of the substrate 30 in a spiral trajectory. The displacement of the substrate 30 being monitored by a controller 31, the location of the measurement zone M on the substrate 30 is known at any time.

[0058] Of course, other scan trajectories are possible, such as a raster scan.

[0059] The angle between the illumination beams 20, 21 is in the range of 10 to 45° for instance, or more specifically 15° to 30°. The beams 20, 21 are contained within an illumination plane forming an angle of incidence with the normal z of the surface of the substrate. The incidence angle can be of any value from a grazing incidence (less than 90°, for example 80°) to normal incidence (0°). Preferably, the incidence angle can be within the ranges of 30° to 75°, or 45° to 60°.

[0060] According to a preferred embodiment, the illumination beams 20, 21 can be coherent with each other. This can be achieved, for example, with a laser source. In this case, an interference pattern is formed in the illumination area M. When a diffracting element on the substrate 30, such as a pit or particle, is illuminated, and this diffracting element moves through the measurement zone M when the substrate 30 is moved relatively to the measurement zone M, the acquired signal will be modulated. The modulation depends on the spatial period of the interference pattern and the speed of the scan of the measurement zone M. Thanks to the modulation, the signal-to-noise ratio (SNR) of the detected signal and thus the precision of the spatial localization, in particular in depth, of the scattering element can be improved.

[0061] In the following, different detection schemes for the inspection device according to embodiments of the present invention will be described with reference to FIGURES 3 to 7.

[0062] FIGURE 3 is a schematical representation of an example of an inspection device according to the present invention.

[0063] The inspection device 100, as represented in FIGURE 3, comprises an illumination module 10, indicated by a dotted line 10 and producing a measurement zone M on the substrate 30.

[0064] The inspection device 100 also comprises a collection lens 40 with a nanostructured surface, which collects the light issued from the substrate 30 and directs it to three different detectors 51, 52, 53.

[0065] The nanostructured surface of the collection lens 40 comprises a plurality of collection sections, or collection regions, each of which is adapted to collect the light issued from the substrate under a given solid angle and to direct that collected light towards one of the detectors 51, 52, 53.

[0066] A light collection region on the nanostructured surface and a corresponding detector form a collection channel. In the example of FIGURE 3, three different collection channels 61, 62, 63 are shown. Indeed, light in three different solid angles 81, 82, 83 is collected and directed to its corresponding detector 51, 52, 53.

[0067] A first collection channel 61 collects the light under a solid angle 81 close to the normal z of the surface. This collection channel 61 corresponds to narrow-angle scattering.

[0068] A second collection channel 62 collects the light according to a solid angle 82 in the backward direction relative to the direction of illumination 10. This collection channel 62 corresponds to wide-angle backward scattering.

[0069] A third collection channel 63 collects the light according to a solid angle 83 in the forward direction. This collection channel 63 corresponds to wide-angle forward scattering.

[0070] As a matter of example, the first collection channel 61 may collect light issued from the illumination area M under a solid angle 81 corresponding to a polar angle range θ of 0° - 10° and an azimuthal angle range φ of 0 - 360°; the second collection channel 62 may detect light under a solid angle 82 corresponding to a polar angle range θ of 60° - 89°, and an azimuthal angle range φ of 0° - 180° or less; the third collection channel 63 may detect light under a solid angle 83 corresponding to a polar angle range θ of 60° - 89°, and an azimuthal angle range φ of 180° - 360° or less.

[0071] In the embodiment shown in FIGURE 3, the nanostructured surface is configured for collimating the collected light in the different light collection sections such that the collected light exiting the collection lens 40 in a collection channel propagates as a collimated beam or in a parallel manner towards the detectors 51, 52, 53. In addition, for at least some of the collection channels, the nanostructured surface can be configured so that the collimated light exits the nanostructured surface perpendicularly, as illustrated.

[0072] The inspection device 100 further comprises focusing lenses 71, 72, 73 adapted to focus the collected light onto the respective detectors 51, 52, 53.

[0073] Each detector 51, 52, 53 of the inspection device 100 produces an inspection signal from the detected light. A processing module (not shown) then produces inspection information from the inspection signals, such as for instance the nature and the size of defects present on or in the substrate, or photoluminescence related information.

[0074] The collected light can comprise scattered or diffracted light having the same wavelength as the illumination light.

[0075] The collected light can also comprise photoluminescence light, emitted at wavelengths different from the illumination wavelength. In this case, the nanostructured surface is configured to direct only the light at some or all of the photoluminescence wavelengths towards the detectors. Light at the illumination wavelength is not directed towards the detectors.

[0076] In order not to detect the specular reflection of the illumination light on the surface of the substrate, the inspection device can be in a dark-field configuration such that none of this specular reflection reaches the detectors.

[0077] A bright-field configuration may also be implemented. In this case, the light from the specular reflection on the substrate’s surface is collected and detected, alone or along with some scattered and/or diffracted light. The specular reflection can, for instance, provide information about the surface of the sample.

[0078] FIGURE 4 is a schematical representation of a further example of an inspection device according to the present invention.

[0079] The inspection device 200, as represented in FIGURE 4, is similar to the inspection device 100 according to the embodiment represented in FIGURE 3.

[0080] The device 200 represented in FIGURE 4 differs from to the device 100 of FIGURE 3 in that it does not comprise focusing lenses. The light collected by the collection lens 40 within the respective collection channels and issuing from the nanostructured surface is directly focused by that nanostructure surface onto the respective detectors 51, 52, 53.

[0081] FIGURE 5 is a schematical representation of another example of an inspection device according to the present invention.

[0082] The inspection device 300, represented in FIGURE 5, is similar to the inspection device 100 according to the embodiment represented in FIGURE 3. It comprises two collection channels 64, 65. A first collection channel 64 is a narrow-angle collection channel for detecting the light issued in a small solid angle 84 around the normal z of the surface of the substrate 30. The inspection device 300 differs from the inspection device 100 in that the second collection channel is a wide-angle collection channel for detecting the light issued in a solid angle 85 corresponding to a ring covering all wide angles in azimuth.

[0083] As a matter of example, the first collection channel 64 may collect light issued from the illumination area M under a solid angle 84 corresponding to a polar angle θ range of 0° - 10° and an azimuthal angle range of 0 - 360°; The second collection channel 65 may detect light under a solid angle 85 corresponding to a polar angle range θ of 60° - 89°, and an azimuthal angle range φ of 0° - 360°.

[0084] As with the embodiment represented in FIGURE 3, the nanostructured surface is configured for collimating the collected light in the different light collection sections such that the collected light propagates in a parallel manner towards the detectors 54, 55. The inspection device 300 further comprises focusing lenses 74, 75 for focusing the collected light onto the respective detectors 54, 55. In that configuration, the nanostructured surface is configured so as to direct the light of the different collection channels in different directions to allow an easier placement of the detectors.

[0085] The inspection device 300 also comprises focusing lenses 74, 75 adapted to focus the collected light onto the respective detectors 54, 55.

[0086] FIGURE 6 is a schematical representation of a further example of an inspection device according to the present invention.

[0087] The inspection device 400, represented in FIGURE 6, is similar to the inspection device 300 according to the embodiment represented in FIGURE 5. It comprises two collection channels corresponding to a narrow-angle and a wide-angle collection channel corresponding to a ring covering all wide angles in azimuth, respectively. The inspection device 400 differs from the inspection device 300 in that each of the two collection channels is divided into two sub-channels 64-1, 64-2, 65-1, 65-2. The light collected under the respective solid angles of the collection channels is separated into two different polarization states in the two sub-channels, respectively. For instance, the light is separated into two linear perpendicular polarization states. Within one collection channel, the light beams with different polarization states are directed towards two different detectors 54-1, 54-2, respectively 55-1, 55-2.

[0088] The polarization separation can be achieved by using birefringent nanostructured surfaces within the different collection sections of the nanostructured surface. Subwavelength-scale structures can be for instance designed to exhibit anisotropic features and thus allow for polarization-dependent control over incident light. In practice, sub-wavelength scale structures may have vastly different responses to orthogonal polarizations of light. Importantly, wavefront phase profile for arbitrary orthogonal polarization states can be controlled simultaneously and independently, by combining propagation and geometric phases of the structures.

[0089] The configuration of the inspection device according to the embodiment illustrated in FIGURE 6 may also be used to separate each of the solid-angle collection channels in two different spectral-range sub-channels. In this case, the nanostructures surfaces of the collection sections are configured so as to exhibit a significant chromatism allowing directing different wavelengths in the collected light in different directions. Owing to current fabrication capacities, subwavelength-scale structures may be realized using a wide range of structure dimensions and orientations to exhibit wavelength dependent features. In particular, such devices are able to split and focus light beams with different wavelengths at different focal points within the same focal plane. In that configuration, the light collected under the respective solid angles of the collection channels is separated into two different spectral ranges or bands in the two sub-channels, respectively. For instance, the light is separated into a visible spectral band and a near-infrared spectral band. Within one collection channel, the light beams with the spectral content within the respective spectral bands are directed towards two different detectors 54-1, 54-2, respectively 55-1, 55-2.

[0090] Such a collection configuration may advantageously be implemented to analyse light issued from photoluminescence within the substrate 30 in different spectral bands.

[0091] For example, defects of monocrystalline SiC such as basal plane dislocations, stacking faults, carrots, etc., generate fluorescence in the visible and the near infrared spectrum when excited with near ultraviolet light (in the range of 280-380 nm). Of course, some of these defects can also generate elastic scattering at the illumination wavelength.

[0092] The inspection device 400 also comprises focusing lenses 74-1, 74-2, 75-1, 75-2 adapted to focus the collected light onto the respective detectors 54-1, 54-2, 55-1, 55-2.

[0093] FIGURE 7 is a schematical representation of another example of an inspection device according to the present invention.

[0094] The inspection device 500, represented in FIGURE 7, is similar to the inspection device 100 in that it comprises three collection channels corresponding to a narrow-angle, a wide-angle forward, and a wide-angle backward collection channel, respectively. Similarly to the inspection device 400, each of the three collection channels 66, 68, 69 is divided into two sub-channels 64-1, 64-2, 66-1, 66-2, 67-1, 67-2. As in the example shown in FIGURE 6, the light collected under the respective solid angles is separated into two different polarization states in the two sub-channels, respectively, and the light beams with different polarization states are directed towards two different detectors 54-1, 54-2, 56-1, 56-2, 57-1, 57-2 within one collection channel.

[0095] The configuration of the inspection device according to the embodiment illustrated in FIGURE 7 may also be used to separate each of the solid-angle collection channels in two different spectral-range sub-channels as described for the device 400 of FIGURE 6.

[0096] The inspection device 500 also comprises focusing lenses 74-1, 74-2, 76-1, 76-2, 77-1, 77-2 adapted to focus the collected light onto the respective detectors 54-1, 54-2, 56-1, 56-2, 57-1, 57-2.

[0097] In FIGURES 3 to 7, the solid wide collection angles are in a ring shape or ring-portions shape.

[0098] Of course, a collection channel may be divided into more than two sub-channels for polarization or spectral discrimination of the collected light.

[0099] FIGURES 8a to 8d show schematical illustrations of embodiments of the nanostructured surface 90 of the collection lens of the inspection device according to the invention. Depicted are various possible arrangements of different collection sections, or regions, of the nanostructured surface. In FIGURES 8a to 8d, the nanostructured surface is of circular form. Other forms are, of course, possible.

[0100] In FIGURE 8a, a central section 91 corresponds to narrow-angle collection. Two peripheral sections 92, 93 are provided, corresponding to forward and backward wide-angle collection, respectively. A ring-shaped section 94 without any nanostructures allows for the transmission of the illumination beam or beams through the collection lens.

[0101] The different sections of the nanostructured surface each represent a metalens, some of which are off axis.

[0102] The collection section arrangement as illustrated in FIGURE 8a may, for example, be implemented in an inspection device according to the embodiments represented in FIGURES 2, 3, and 7.

[0103] In FIGURE 8b, a central narrow-angle collection section 95 is surrounded by a ring-shaped wide-angle collection section 96. The nanostructured surface 90 also comprises a small area 97 between the collection sections 95, 96 without any nanostructures allowing the illumination beam to pass through the collection lens.

[0104] In FIGURE 8c, a central section 91 corresponds to narrow-angle collection. One peripheral section 92’ corresponding to both forward and backward wide-angle collection is provided. A ring-shaped section 94 without any nanostructures allows for the transmission of the illumination beam or beams through the collection lens.

[0105] The collection section arrangements as illustrated in FIGURES 8b and 8c, for example, be implemented in an inspection device according to the embodiments represented in FIGURES 5 and 6.

[0106] In FIGURE 8d, the circular surface is divided into eight equal sections 98, which may have different functions.

[0107] Of course, other configurations of the nanostructured surface are possible.

[0108] The inspection device of the invention according to its various embodiments may be realized with nanostructured surfaces, or metasurfaces designed and manufactured according to various methods known in the prior art.

[0109] Advantageously, the invention exploits the large flexibility which is offered by the design and manufacturing possibilities of these nanostructured surfaces. In particular, a complex nanostructured surface with various sectors, each having its specific light conditioning capabilities is manufactured, as illustrated for example in FIGURES 8a-8d.

[0110] The nanostructured surfaces as used in the invention, also called optical metasurfaces, are composed of subwavelength structures designed and arranged in specific patterns at the interface between two media or on top of a substrate. These ultrathin components are able to alter every single aspect of transmitted or reflected light beams, and notably control phase, amplitude, and polarization. They can be designed to operate in monochromatic or polychromatic modes. Their basic operational principle is related to the collective scattering of light by an ensemble of subwavelength optical elements with different spectral and polarization responses. According to Huygens's construction, each element of a wavefront may be regarded as a centre of a secondary disturbance, which gives rise to spherical wavelets; the wavefronts at any later time are given by the superposition of all such wavelets. By designing each element to give rise to a tailored phase shift for the respective wavelet, the wavefronts after the metasurface can have any desired structure. Importantly, these elements may be realized, thanks to state-of-the-art fabrication methods, to continuously change their functionality within the metasurface without, or with negligible, discrepancies at borders of two zones.

[0111] Based on this concept, various metasurfaces with optical functionalities relevant to this invention can be realized, based on techniques known in the literature. The literature describes metasurfaces to achieve arbitrary reflection and refraction to focus or collimate light, including off the optical axis, or such metasurfaces with dependence on the polarization or providing spectral control. A list of such references is provided below:

- M. Khorasaninejad, W. T. Chen, J. Oh, and F. Capasso, "Super-Dispersive Off-Axis Meta-Lenses for Compact High Resolution Spectroscopy", Nano Lett. 16 (6), pp. 3732–3737 (2016)
- M. Khorasaninejad, W. T. Chen, J. Oh, and F. Capasso, "Super-Dispersive Off-Axis Meta-Lenses for Compact High Resolution Spectroscopy", Nano Lett. 16 (6), pp. 3732–3737 (2016)
- M. Khorasaninejad, W. T. Chen, A. Y. Zhu, J. Oh, R. C. Devlin, D. Rousso, and F. Capasso, "Multispectral Chiral Imaging with a Metalens", Nano Lett. 2016, 16, pp. 4595−4600
- Qinghua Song, Xingsi Liu, Cheng-Wei Qiu, and Patrice Genevet, "Vectorial metasurface holography", Appl. Phys. Rev. 9, 011311 (2022)
- Yuhang Sun, Yumin Liu , Tiesheng Wu, Jing Li , Hongjie Fan, Xueyu Wang, "Polarization-dependent metalens with flexible and steerable bifocal spots", Results in Physics 46, March 2023, 106286
- Mohammad Sadegh Faraji-Dana, Ehsan Arbabi, Hyounghan Kwon, Seyedeh Mahsa Kamali, Amir Arbabi, John G. Bartholomew, and Andrei Faraon, "Hyperspectral imager with folded metasurface optics", ACS Photonics 2019, 6, pp. 2161−2167
- Wesley A. Britton, Yuyao Chen, Fabrizio Sgrignuoli, and Luca Dal Negro, "Phase-Modulated Axilenses As Ultracompact Spectroscopic Tools", ACS Photonics 2020, 7, 10, 2731–2738

[0112] More specifically, the nanostructured surface implemented with the inspection device according to the present invention is for instance made of materials such that the light transmission is optimized for the illumination, or working, wavelength. For example, for a wavelength of 473 nm, gallium nitride (GaN) deposited on a sapphire substrate may be used. Other materials can be used as long as their refractive index is high enough to confine the light in subwavelength-scale elements or nano resonators, and their transmission for the considered wavelength is high enough to achieve efficiency of the subwavelength-scale elements. In general, the shapes of individual subwavelength-scale elements and the geometry of their pattern on plane can be engineered to enable a metasurface with different optical properties. Mainly, this is a consequence of coupling of light and surface plasmon polariton waves generated at boundaries. For visible wavelengths, silicon carbide (SiC) or titanium dioxide (TiO_2) may be used, and amorphous silicon for near infrared wavelengths. Examples of subwavelength optical elements composing the surface are pillars, or waveguides, of diameter 100nm and height 1μm.

[0113] The solid-angle separation of the collected light is achieved with a specific phase profile of the nanostructured surface.

[0114] The nanostructured surface can be realized for instance using an electron beam for etching the elements or the subwavelength structures forming that nanostructured surface. Any form of optical function, i.e., solid-angle separation, may be obtained by etching a specifically designed pattern of elements on the desired collection region of the collection lens on the metasurface.

[0115] The nanostructured surface may comprise one layer of subwavelength-scale elements. It may also comprise a plurality of layers, each comprising subwavelength-scale structures. In that case, materials of different indices of refraction, such as oxide and nitride, deposited side by side to form a layer, can realize the subwavelength-scale structures.

[0116] The area outside or between the collection regions may be designed to be absorbing or reflecting by using different resonators working in the corresponding regimes, or even in transmission but with a different phase profile so that the light in these regions is redirected out of the detectors.

[0117] Form-birefringent nanostructured surfaces offer polarization dependent control of incident light. By adjusting the geometry and the orientation of anisotropic elements, the polarization of the collected light can be converted and/or filtered. This functionality can be achieved simultaneously and independently of the phase profile of the whole metasurface. Therefore, the solid-angle division and the polarization control functionalities can be combined without reducing the effectiveness of either of them.

[0118] Of course, the invention is not limited to the examples detailed above.

CLAIMS

1. An inspection device (100, 200, 300, 400, 500) for detecting defects on substrates, such as wafers, comprising:

- an illumination module (10) comprising at least one light source (12) configured to illuminate at least one region of a substrate (30) to be inspected with at least one illumination beam (20, 21);
- at least one detector (51, 52, 53, 54, 54-1, 54-2, 55, 55-1, 55-2, 56-1, 56-2) configured to detect light issued from the substrate (30) and to produce an inspection signal;
- a light collection module; and
- a processing module configured to produce an inspection information from the inspection signal,

wherein the light collection module comprises at least one collection lens (40) with a nanostructured surface (90), the nanostructured surface (90) comprising at least one light collection region (91, 92, 92', 93, 94, 95, 96, 97, 98) configured to collect light issued from the substrate (30) within a predetermined solid angle (81, 82, 83, 84, 85) and to direct the collected light towards a corresponding detector (51, 52, 53, 54, 54-1, 54-2, 55, 55-1, 55-2, 56-1, 56-2), a light collection region and a corresponding detector forming a collection channel (61, 62, 63, 64, 65, 66, 67, 68).

2. The inspection device (100, 200, 300, 400, 500) according to claim 1, characterized in that it comprises at least two collection channels (61, 62, 63, 64, 65, 66, 67, 68), the collection channels corresponding to different solid angles (81, 82, 83, 84, 85).

3. The inspection device (100, 200, 300, 400, 500) according to claim 1 or 2, characterized in that the collection channel comprises a plurality of polarization sub-channels (64-1, 64-2, 65-1, 65-2, 66-1, 66-2, 67-1, 67-2), each corresponding to a different polarization of the light issued from the

substrate (30), the light of each polarization sub-channel being directed in a different direction.

4. The inspection device (100, 200, 300, 400, 500) according to the preceding claim, characterized in that the polarization sub-channels (64-1, 64-2, 65-1, 65-2, 66-1, 66-2, 67-1, 67-2) are implemented by a birefringent nanostructured surface (90) of the collection lens (40).

5. The inspection device (100, 200, 300, 400, 500) according to claim 1 or 2, characterized in that the collection channel comprises a plurality of chromatic sub-channels (64-1, 64-2, 65-1, 65-2, 66-1, 66-2, 67-1, 67-2), each corresponding to a different spectral range of the light issued from the substrate (30), the light of each chromatic sub-channel being directed in a different direction.

6. The inspection device (100, 200, 300, 400, 500) according to the preceding claim, characterized in that the chromatic sub-channels (64-1, 64-2, 65-1, 65-2, 66-1, 66-2, 67-1, 67-2) are implemented by a chromatic nanostructured surface (90) of the collection lens (40).

7. The inspection device (100, 200, 300, 400, 500) according to any one of the preceding claims, characterized in that the collection lens (40) comprises a region (94, 97) without nanostructures such that the illumination light passes through that region of the collection lens to illuminate the substrate (30).

8. The inspection device (100, 200, 300, 400, 500) according to any one of the preceding claims, characterized in that the illumination module (10) and the at least one detector (51, 52, 53, 54, 54-1, 54-2, 55, 55-1, 55-2, 56-1, 56-2) are configured to operate in a dark-field configuration.

9. The inspection device (100, 200, 300, 400, 500) according to any one of claims 1 to 7, characterized in that the illumination module (10) and the at least one detector (51, 52, 53, 54, 54-1, 54-2, 55, 55-1, 55-2, 56-1, 56-2) are configured to operate in a bright-field configuration.

10. The inspection device (100, 200, 300, 400, 500) according to any one of the preceding claims, characterized in that the collection module comprises a focusing lens (71, 72, 73, 74, 74-1, 74-2, 75, 75-1, 75-2, 76-1, 76-2, 77-1, 77-2) for each collection channel (61, 62, 63, 64, 65, 66, 67, 68) configured to focus the collected light on the detector (51, 52, 53, 54, 54-1, 54-2, 55, 55-1, 55-2, 56-1, 56-2), the at least one light collection region being configured to collimate the collected light.

11. The inspection device (100, 200, 300, 400, 500) according to any one of claims 1 to 9, characterized in that the at least one light collection region is configured to focus the collected light on the detector (51, 52, 53).

12. The inspection device (100, 200, 300, 400, 500) according to any one of the preceding claims, further comprising displacement means (22, 31) configured to displace the illuminated region on the substrate (30).

13. The inspection device (100, 200, 300, 400, 500) according to any one of the preceding claims, characterized in that an angle of incidence of the illumination beam on the substrate (30) varies between grazing incidence and normal incidence.

14. The inspection device (100, 200, 300, 400, 500) according to any one of the preceding claims, characterized in that at least two illumination beams (20, 21) intersect each other in the illuminated region on the substrate (30).

15. The inspection device (100, 200, 300, 400, 500) according to the preceding claim, characterized in that two illumination beams (20, 21) form an interference pattern in the illuminated region.

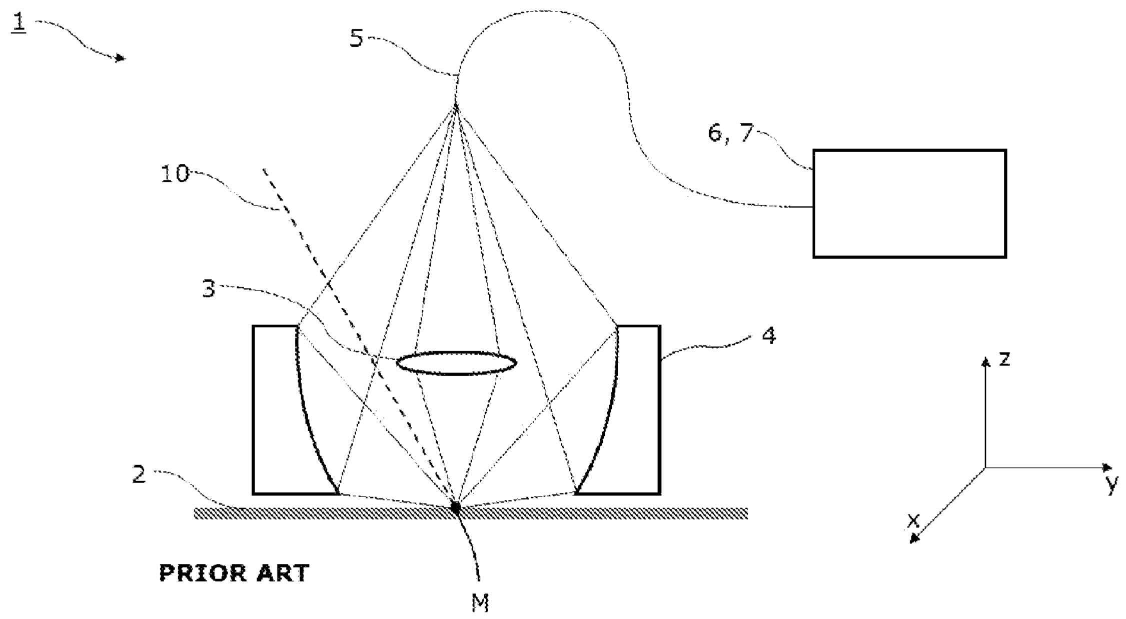
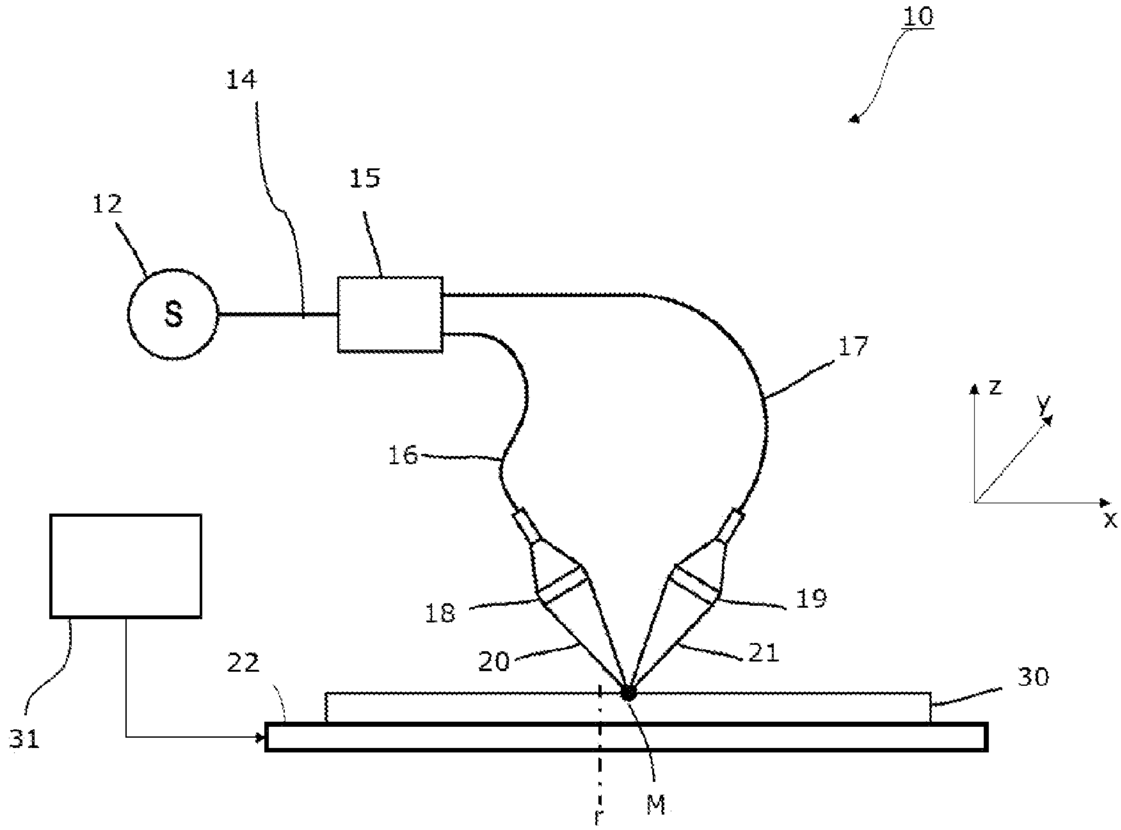

1
5
6, 7
10
3
4
z
y
x
2
PRIOR ART
M

Fig. 1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31
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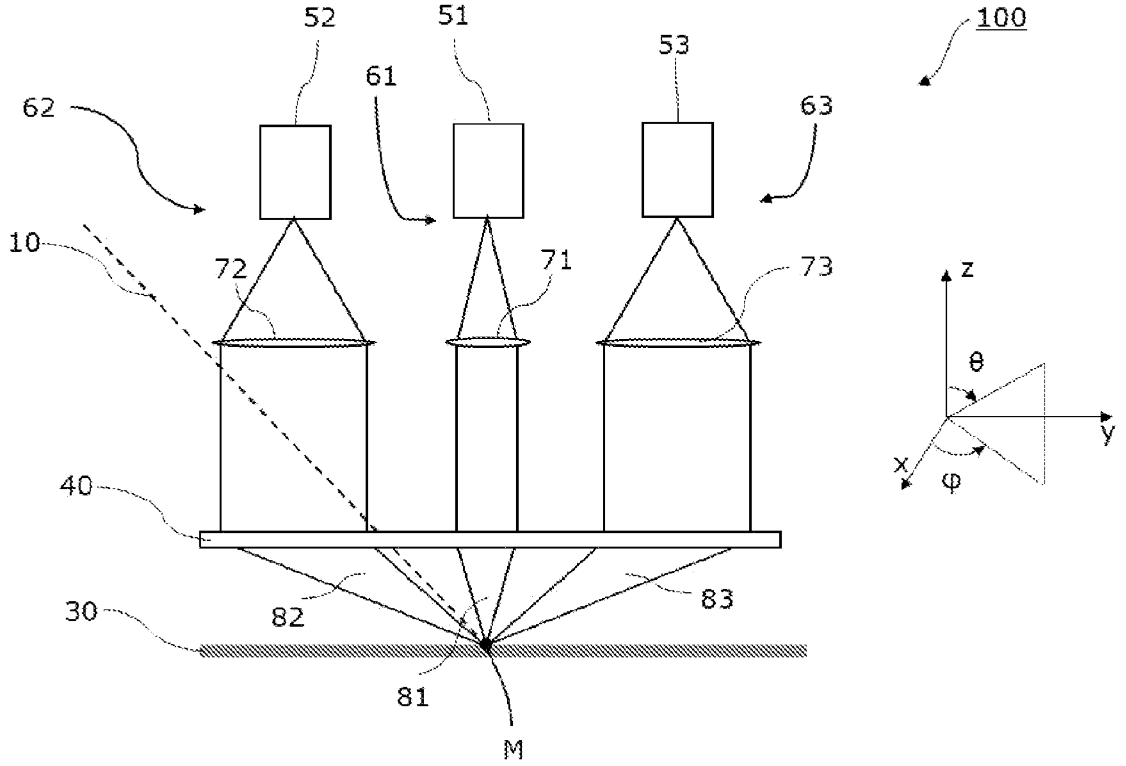
Fig. 2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51
53
100
61
62
63
10
72
71
73
z
θ
y
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φ
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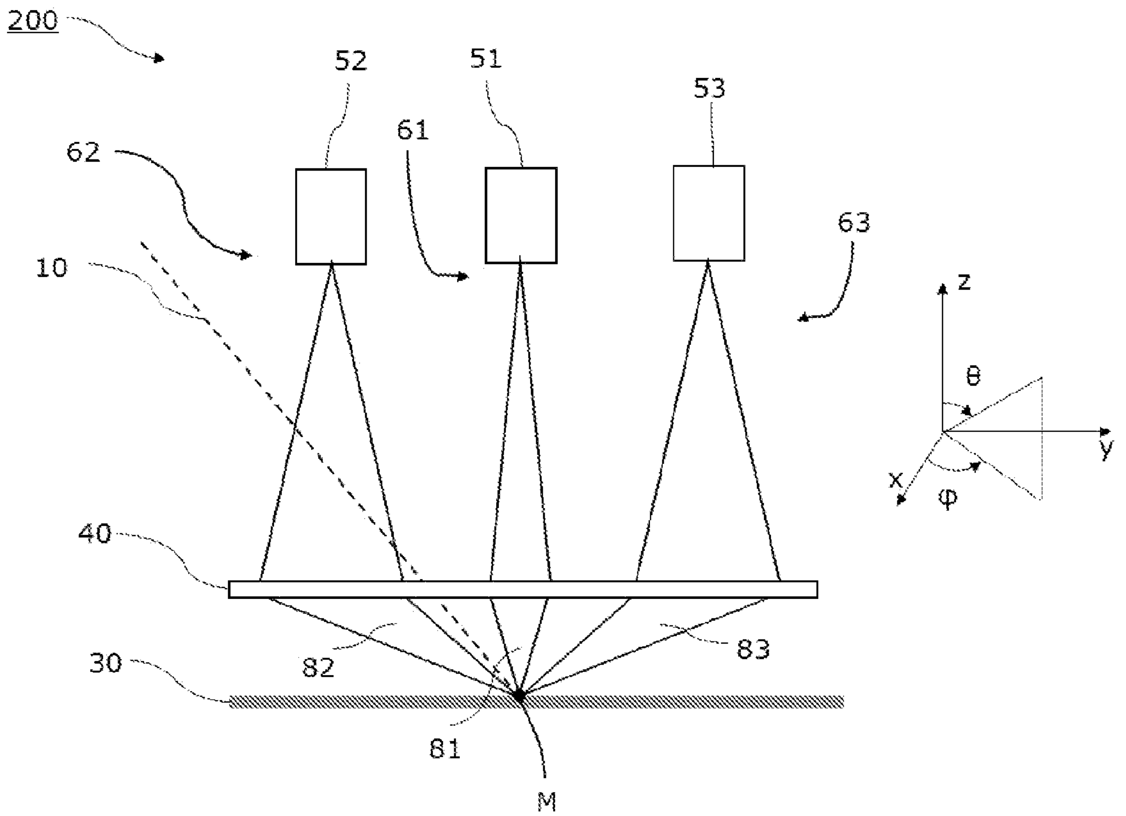
82
83
30
81
M

Fig. 3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62
63
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θ
y
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φ
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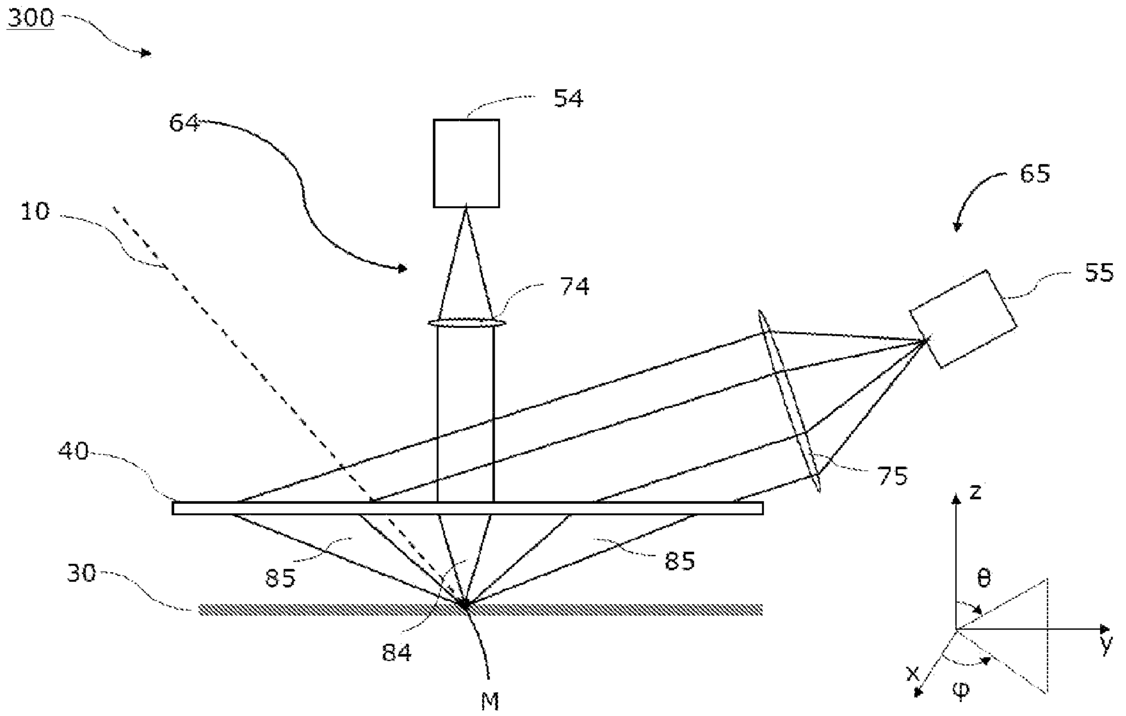
83
30
81
M

Fig. 4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65
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74
55
40
75
z
30
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85
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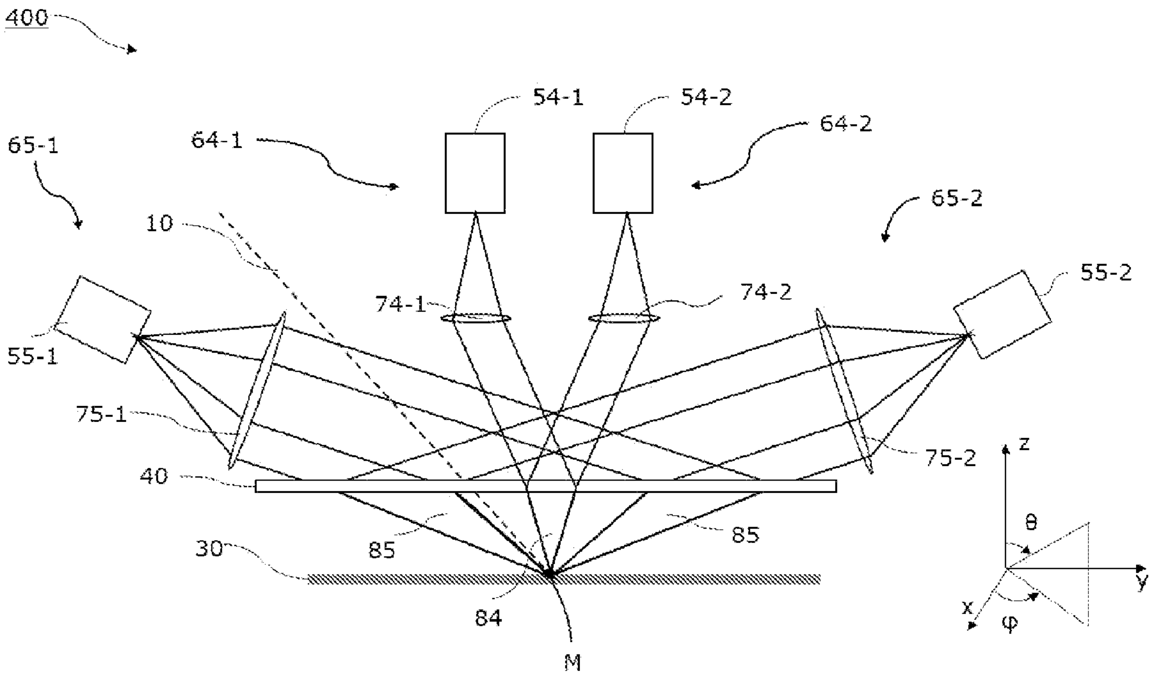
84
x
φ
M

Fig. 5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54-2
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64-1
64-2
65-2
10
55-2
74-1
74-2
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75-1
z
75-2
40
θ
85
85
30
y
x
84
φ
M

Fig. 6

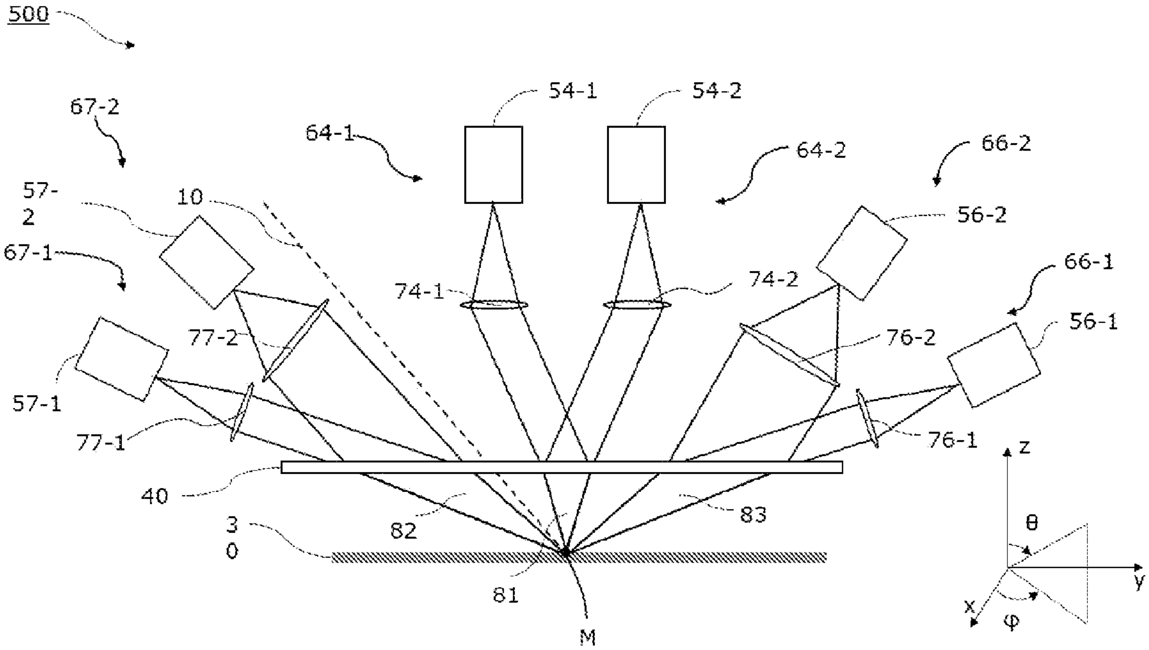

Fig. 7

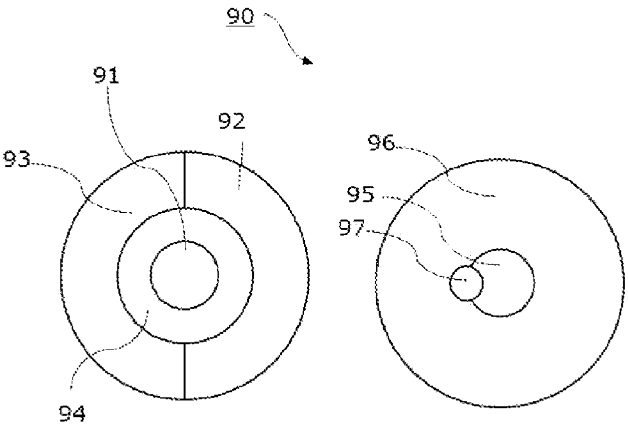

Fig. 8a Fig. 8b

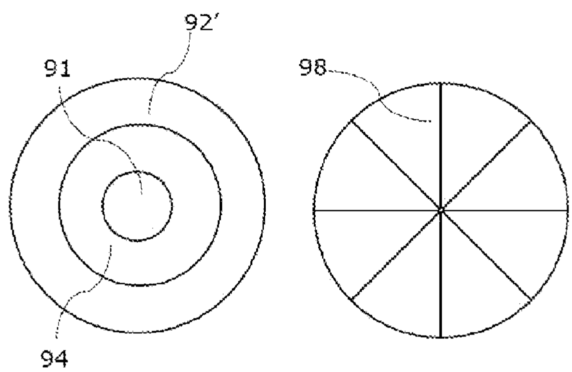

Fig. 8c Fig. 8d

INTERNATIONAL SEARCH REPORT

International application No
PCT/IB2023/000459

A. CLASSIFICATION OF SUBJECT MATTER
INV. G01N21/95 H01L21/66 G01N21/88
ADD.

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
G01N H01L

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

EPO-Internal, WPI Data

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 2022/283516 A1 (SWILLAM MOHAMED [US] ET AL) 8 September 2022 (2022-09-08) paragraphs [0061], [0084], [0088], [0129]; figures 2, 8, 9 -----	1,8, 13-15
X	US 2021/172879 A1 (CHEN GUANGDIAN [CN] ET AL) 10 June 2021 (2021-06-10) paragraphs [0026], [0028], [0029]; figures 1-3 -----	1,10,11
X	FR 3 118 175 A1 (UNITY SEMICONDUCTOR [FR]) 24 June 2022 (2022-06-24) paragraph [0031]; claims 1, 17-20; figure 1 ----- -/--	1,2,5,6, 9,12

[x] Further documents are listed in the continuation of Box C.

[x] See patent family annex.

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Date of the actual completion of the international search	Date of mailing of the international search report
15 December 2023	03/01/2024

Name and mailing address of the ISA/	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Fax: (+31-70) 340-3016	Koll, Hermann

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C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 2021/306564 A1 (HU JUEJUN [US] ET AL) 30 September 2021 (2021-09-30) paragraphs [0014], [0107], [0108], [0111], [0112]; figures 1A, 1B, 10-12 -----	1-6
X	US 2023/099112 A1 (SIDDIQUE RADWANUL HASAN [US] ET AL) 30 March 2023 (2023-03-30) claims 1, 5, 10; figures 1, 2 -----	1,2,5,6
X	US 2020/217796 A1 (SAMSUNG ELECTRONICS CO LTD [KR]) 9 July 2020 (2020-07-09) abstract; claim 1; figures 1-4, 22 -----	1,7

1

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No
PCT/IB2023/000459

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
US 2022283516 A1	08-09-2022	CN 114303100 A	08-04-2022
		TW 202113464 A	01-04-2021
		TW 202201120 A	01-01-2022
		US 2022283516 A1	08-09-2022
		WO 2021037509 A1	04-03-2021
US 2021172879 A1	10-06-2021	CN 111065912 A	24-04-2020
		TW 202122785 A	16-06-2021
		US 2021172879 A1	10-06-2021
		WO 2021109012 A1	10-06-2021
FR 3118175 A1	24-06-2022	FR 3118175 A1	24-06-2022
		WO 2022129721 A1	23-06-2022
US 2021306564 A1	30-09-2021	AU 2020324338 A1	03-03-2022
		CA 3146753 A1	11-02-2021
		CN 114341674 A	12-04-2022
		EP 4010742 A1	15-06-2022
		IL 290397 A	01-04-2022
		JP 2022544213 A	17-10-2022
		KR 20220042406 A	05-04-2022
		US 2021044748 A1	11-02-2021
		US 2021306564 A1	30-09-2021
		WO 2021025759 A1	11-02-2021
US 2023099112 A1	30-03-2023	KR 20210093154 A	27-07-2021
		US 2021223104 A1	22-07-2021
		US 2023099112 A1	30-03-2023
US 2020217796 A1	09-07-2020	EP 3677902 A1	08-07-2020
		KR 20200084690 A	13-07-2020
		US 2020217796 A1	09-07-2020